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FAULT TROUGHS[1]

STEPHEN TABER
University of South Carolina

ABSTRACT

Fault troughs may be classed as superficial or profound. Superficial fault troughs result from (1) earthquakes, or (2) volcanic activity, or (3) tension. Tensional fault troughs are due to differential uplift, rotational strain, or the tilting of large fault blocks. The differential uplift may be caused by igneous intrusions and by the relative displacement of large rigid fault blocks underlying sedimentary formations. The faults associated with very large fault troughs extend to profound depths and reach the zone of flowage. Evidence bearing on their origin is less conclusive than that for superficial troughs. Several factors have probably entered into their formation, but tension, resulting in normal faulting and an upward tilting of the inclosing masses, is probably most important. Extrusion of lavas and increase in density, due to expulsion of gases and the crystallization of magmas, have played a more or less important part in some instances. Large troughs have probably developed in part along pre-existing faults. Illustrations are given of the different types of fault troughs.

INTRODUCTION

A fault trough is usually defined as a rock mass lying between more or less parallel faults or fault zones and depressed relative to the masses on each side. It has been generally assumed that the faults are normal in type and therefore converge downward, but a few geologists have argued that the main faults are thrust faults. Since flexing is a factor in the formation of many fault troughs, a broader definition seems preferable, and in this paper the term is applied to a structural trough due chiefly to faulting. The French equivalent is *fosse*, and the German is *graben*.

[1] Presented in part at a meeting of the South Carolina Academy of Science, March 26, 1925.

In 1894 Gregory[1] introduced the term *rift valley* to designate a valley formed by trough faulting, and it has come into wide use. Some geologists have referred to valleys cut by erosion in fault troughs, or even along faults, as rift valleys, but in this paper the stricter usage will be followed.

The literature on fault troughs is extensive, but it is practically confined to descriptions of individual occurrences. Most writers have assumed that all fault troughs have had the same origin, and no detailed, comparative study of these structures seems to have been made. Weber, who probably made the most extensive investigation, confined himself to the larger fault troughs, and in fact devoted most of his discussion to the *Rhinegraben*.[2]

Until more information is available concerning the origin of fault troughs, especially the large ones, it will be impossible to classify them satisfactorily on a genetic basis. Therefore the classification offered below is regarded as merely tentative.

TENTATIVE CLASSIFICATION OF FAULT TROUGHS

I. Superficial Fault Troughs
   1. Seismic in Origin
   2. Volcanic in Origin
   3. Tensional in Origin
      (*a*) Due to differential uplift
      (*b*) Due to rotational strain
      (*c*) Due to the tilting of fault blocks

II. Profound Fault Troughs

Some fault troughs are probably intermediate between these types, and with additional information it should be possible to expand and modify the classification. Superficial fault troughs are small, the fault planes extending downward for only a few thousand feet, and therefore seldom reaching the zone of rock flowage, even in weak rocks. Profound fault troughs are larger in every respect, and the faults continue downward to the mobile zone.

[1] J. W. Gregory, "Contributions to the Physical Geography of British East Africa," *Geog. Jour.*, Vol. IV (1894), pp. 290–315, 408–24, and 505–14.

[2] Maximilian Weber, "Zum Problem der Grabenbildung," *Zeitschrift der Deutschen Geologischen Gesellschaft*, Bd. 73 (1921), pp. 238–91.

SEISMIC FAULT TROUGHS

The small fault troughs and depressions commonly found along the outcrops of active faults and formed at the time of great earthquakes were discussed in a previous paper.[1] They were attributed to the downfaulting of narrow blocks, or wedges, within a belt of parallel and interlacing fractures; the settling of the wedges taking place while the rocks were momentarily separated by the passage of earthquake vibrations.

Fault troughs of this type develop where the displacement is dominantly horizontal, as on the San Andreas fault of California, and also where it is chiefly vertical, as on the Aasatch fault of Utah. Troughs formed at the time of the Owens Valley earthquake of 1872 ranged up to several hundred yards in length and were as much as 200 or 300 feet in width, the inclosing scarps having a maximum height of 10 and 20 feet. Somewhat larger troughs undoubtedly originate in the same way, but not those having a width of several miles.

Sections across downfaulted wedges of this type have been exposed by mining operations and by erosion; especially fine illustrations are found in the lower part of the Grand Canyon of the Colorado, where the Algonkian strata are cut by the West Kaibab fault zone and by other great faults. Noble has photographed and described one of these wedges, every detail of which "is revealed from its summit, where it is truncated by the pre-Tonto [pre-Cambrian] unconformity down to its apex, a vertical distance of 1,000 feet."[2] The harder rocks along the faults in places have been crushed and cemented to form a breccia.

The small fault troughs occurring along fault zones are accessory structures; their formation results from recurring displacements along major faults, and is not a cause of faulting. They are a result rather than a cause of earthquakes. This type of trough may accompany other types, especially the large ones.

[1] Stephen Taber, "Some Criteria Used in Recognizing Active Faults," *Bulletin Geological Society of America*, Vol. XXXIV (1923), p. 668.

[2] L. F. Noble, "The Shinumo Quadrangle, Grand Canyon District, Arizona," *U. S. Geological Survey Bulletin 549* (1914), p. 77 and Plate XV, B, p. 64.

It is probable that seismic fault troughs are not entirely limited to fault zones, and that they may occasionally be formed by the dropping of V-shaped blocks bounded by master joints, as advocated by W. O. Crosby and Irving B. Crosby;[1] but it is unfortunate that in the type examples cited by them no positive evidence of downward displacement has been given. Moreover, it is difficult to understand why such phenomena should be so plentiful in the New England states, where the seismicity is relatively low, when they have not been observed in regions of high seismicity, such as central and southern California.

In the epicentral areas of great earthquakes visible waves have often been observed. Such waves necessarily have a large amplitude, short wave-length, and low velocity. I have given evidence that the dropping of keystones in arches at Stanford University during the earthquake of 1906 was caused by the passage of earth-waves,[2] and there is no obvious reason why wedges of rock within the earth's crust could not similarly be dropped. But at a relatively short distance from the epicentral area the wave-length increases and the amplitude decreases to such an extent as to preclude this as a cause of the downfaulting of wedge-shaped blocks.

Seismic fault troughs may not be distinguishable in some cases from similar troughs resulting from tension, though the latter are usually larger. Also, the formation of some fault troughs must be attributed to a combination of factors.

VOLCANIC FAULT TROUGHS

Volcanic fault troughs are formed by the subsidence of long narrow blocks within a fracture zone because of lava movements a short distance below the surface. They are superficial phenomena and are probably confined very largely to decadent volcanoes. The subsidence results in faulting, which is accompanied by local earthquakes.

This type is well illustrated by a fault trough at the eastern end of the Island of Hawaii, within the northeastern fault system of

[1] W. O. Crosby and Irving B. Crosby, "Keystone Faults," *Bulletin Geological Society of America*, Vol. XXXVI (1925), pp. 623–40.

[2] Stephen Taber, "Some Local Effects of the San Francisco Earthquake," *Journal of Geology*, Vol. XIV (1906), pp. 312–15.

Kilauea, which was deepened in April, 1924. The fault block is about a mile wide, and the subsidence, which took place gradually over a period of several days, amounted to 10 or 12 feet on the northeast side and a foot or two on the opposite side. The movement extended for 4 or 5 miles along the length of the block, and at its seaward end resulted in the formation of a new lagoon 200 feet long and 6–8 feet deep. At one place a subsidiary trough was formed where a block of ground 20 feet wide sank 6 feet. The superficial nature of the displacement is indicated by the fact that the earthquakes were not felt at Kalapana, 12 miles to the southwest, and were only slightly felt at a point a few hundred feet north of the fault block.[1]

The subsidence of the floor of the Valley of Ten Thousand Smokes near Mount Katmai, Alaska, in 1912, which amounted to 200 feet, has been attributed to the escape of lava following the intrusion of a sill.[2]

The formation of volcanic fault troughs is a cause of earthquakes, and not a result. In this respect they differ from seismic fault troughs. The earthquakes, however, are local in character.

TENSIONAL FAULT TROUGHS DUE TO DIFFERENTIAL UPLIFT

Fault troughs associated with anticlines, domes, and monoclinal flexures are formed at or near the surface and do not extend to great depth. They are commonly between one-fourth mile and one mile in width; rarely as much as two miles. In the larger ones the dropped blocks are usually broken by strike faults.

Excellent illustrations of this type of fault trough are found in the Colorado Plateau region in Emery, Sevier, and Grand counties, Utah (see map, Fig. 1). Much of the area has not been mapped in detail, but enough work has been done to establish the main facts concerning the geologic structure.

In the southeast quarter of Grand County there is a pronounced anticlinal axis striking N. 45° W. It passes through Salt Wash on

[1] T. A. Jaggar, *Monthly Bulletin of the Hawaiian Volcano Observatory*, Vol. XII (1924), pp. 17–23.

R. H. Finch, "Seismic Sequences of the Explosive Eruption of Kilauea in May, 1924," *Bulletin Seismological Society of America*, Vol. XIV (1924), pp. 217–22.

[2] Clarence N. Fenner, "Earth Movements Accompanying the Katmai Eruption," *Journal of Geology*, Vol. XXXIII (1925), pp. 193–223.

the northwest side of the Grand River, continues up Castle Valley on the southeast side toward the northern group of the La Sal Mountains, and, according to Hill, is apparently seen again southeast of these mountains in the Paradox Valley of Colorado.[1]

The La Sal Mountains are of the laccolithic type, the intrusive cores consisting of monzonite or diorite porphyry. The sedimentary

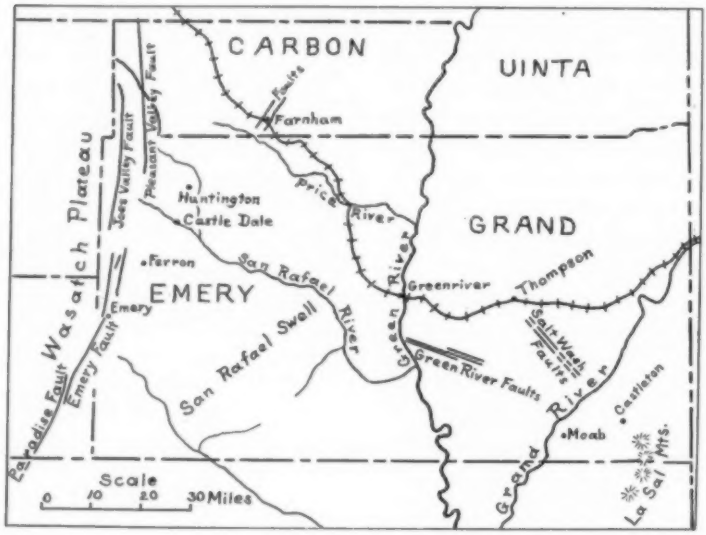

FIG. 1.—Faults in eastern Utah

beds are upturned around the flanks of the northern mountains. Salt Wash is a valley of erosion, cut, in part at least, in a fault trough formed in the crest of the anticline. Dake[2], describing this trough under the name of Valley City *graben*, states that a block about one mile wide has been dropped 1,200 feet or more. His section across the trough is reproduced in Figure 2. He mapped the trough for a distance of 6 miles, but it may continue farther, es-

[1] J. M. Hill, "Notes on the Northern La Sal Mountains, Grand County, Utah," *U. S. Geological Survey Bulletin 530* (1911), pp. 108–9.

[2] C. L. Dake, "The Valley City *Graben*, Utah," *Journal of Geology*, Vol. XXVI, (1918), pp. 569–73.

pecially toward the southeast. Near the inclosing scarps the downfaulted beds show high local dips that are probably due to drag along the fault planes.

Hill states that Castle Valley is 2 miles wide and 9 miles long, with a flat floor except for a round porphyry butte near the center.

FIG. 2.—Section across Valley City fault trough. After C. L. Dake

He does not attribute the valley to faulting, but mentions a fault just east of the river with displacement of 100 feet.[1]

Dake suggests the presence of a similar fault trough along the crest of the parallel anticline at Moab, which has its apex in the southern group of the La Sal Mountains.

Two fault troughs in the western part of Grand County, near the Green River, have been mapped by Lupton.[2] They are part of a single fault system formed by the rupturing of beds along a sharp

FIG. 3.—Section across Green River fault trough. After C. T. Lupton

flexure on the flank of a northeastward-dipping monocline. Both downfaulted blocks are about one-half mile wide, and they have their beds upturned by drag along the boundary faults. The trough nearest the river has an average strike of N. 75° W. for a distance of 9 miles or more, the rocks within it being dropped a maximum of 500 feet, while the strata on the north side stand 300 feet above those on the south (see Fig. 3). The other trough, having the same strike, lies to the northeast of and overlaps the first. It has been traced about 6 miles and has a maximum downthrow of 400 feet.

[1] J. M. Hill, *op. cit.*, pp. 106–9.

[2] C. T. Lupton, "Oil and Gas near Green River, Grand County, Utah," *U. S. Geological Survey Bulletin 541* (1912), pp. 115–33.

The Pleasant Valley anticline, a low domelike uplift, which extends from the northwest corner of Emery County northward across the west end of Carbon County, has been described by Taff.[1] A large fault with north-south trend follows approximately along the axis of the anticline and has been traced for over 30 miles. The displacement is variable, in places reaching 1,000 feet. The fault-plane, where exposed, dips at a steep angle toward the east or downthrow side. A dropped block, lying between the Pleasant Valley fault on the west and several step faults that parallel it less than two miles to the east, is exposed in Huntington Canyon. The length of the fault trough is unknown.

Little information is available about the Joes Valley fault system which lies 5–6 miles west of the Pleasant Valley fault, but Taff gives evidence of trough faulting along it.[2]

West of Ferron and Emery in Emery County, a group of normal faults bearing north and south cut the escarpment of the Wasatch Plateau. They have been described by Taff, who states that a block of faulted strata $1\frac{1}{2}$–3 miles in width, supposedly Tertiary in age, has been let down about 300 feet into Laramie sandstone.[3]

Farther south along the western side of Castle Valley and adjacent to the Wasatch Plateau are two important faults which have been mapped and described by Lupton,[4] the Emery fault and the Paradise fault. The Emery fault has been traced for 20 miles in a northeast-southwest direction and shows a maximum displacement of about 2,000 feet. In a faulted zone along the west side of Emery fault a trough fault has been formed by the dropping of a block of Mesaverde rocks. The block is broken into smaller blocks by strike faults. This fault system is apparently continuous with that west of Ferron, and the system may extend far enough north to connect up with the Pleasant Valley and Joes Valley faults. The Paradise fault extends along the west side of the dropped block, and according to

[1] J. A. Taff, "The Pleasant Valley Coal District, Carbon and Emery Counties, Utah," *U. S. Geological Survey Bulletin 316* (1916), pp. 338–58.

[2] *Ibid.*, p. 345.

[3] J. A. Taff, "Book Cliffs Coal Field, Utah, West of Green River," *U. S. Geological Survey Bulletin 285* (1905), p. 293.

[4] C. T. Lupton, "Geology and Coal Resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah," *U. S. Geological Survey Bulletin 628* (1916), pp. 41–43.

Lupton it probably connects with the Mille Lac (Thousand Lake) fault described by Gilbert.[1]

Throughout most of the Castle Valley district, lying between the San Rafael Swell and the Wasatch Plateau, the prevailing dip is at low angles toward the west, but at several places the beds are disturbed by small local upfolds and domes. The Farnham upfold, an elliptical anticline 4–5 miles long from north to south and about 2 miles wide, is on each side cut by "strike faults having displacements of as much as 300 feet, with the upthrow side next to the axis." Some of the domes are nearly circular.[2] The San Rafael Swell itself is a large domelike uplift.

Although trough faulting is a characteristic of the plateau region in Emery and Grand counties, true rift valleys (tectonic valleys) are absent, the valleys now occupying the fault troughs being products of erosion. Rift valleys were probably formed as a result of the faulting, but have been removed by erosion. This is in accord with the relatively low seismicity which the region now appears to have.

The major structural features of the region are due to differential uplift rather than tangential compression, for the axes of folding, instead of being parallel, are oriented in different directions, and most of the anticlines are markedly quaquaversal, while some are almost circular domes.

The differential uplift was probably, in part at least, due to the intrusion of igneous magma. The Henry, La Sal, and Abajo mountain groups, lying near the southern border of the area, are all laccolithic in origin. The northern La Sal Mountains apparently form the apex of one of the prominent faulted anticlines, while the southern group form the apex of a parallel anticline. Igneous dikes are not common along the faults, except locally, and should not be in a region where laccoliths and sills are the characteristic forms of intrusion, and where erosion has not removed most of the covering strata. At the Winterquarters mine near Schofield, however, thin igneous dikes associated with short east-west faults were observed by Taff.[3]

[1] G. K. Gilbert, "Report on the Geology of the Henry Mountains," *U. S. Geog. and Geol. Survey of the Rocky Mountain Region* (1877), Plate II.

[2] C. T. Lupton, "Geology and Coal Resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah," *U.S. Geological Survey Bulletin 628* (1916), pp. 40–41.

[3] *Op. cit.*, p. 293.

The monoclinal flexures and some of the large asymmetrical anticlines of the plateau region should probably be attributed to the differential displacement and tilting of large fault blocks which are composed of relatively rigid crystalline rocks, and are covered with a veneer of sedimentaries having a thickness of not more than 2 or 3 miles.

In a recent paper Laurence M. Gould,[1] discussing the origin of laccolithic intrusions with especial reference to the La Sal Mountains, suggests that the anticlinal structure preceded intrusion, and cites as evidence the absence of great tensional effects and the persistence of the arches, together with the absence of igneous rocks in association with them.

The Valley City fault trough on the crest of part of the northern La Sal Mountains arch is certainly evidence of tension, though it is not referred to by Gould. The La Sal Mountains laccoliths, according to Gould, were intruded chiefly at the horizon of the Cutler (Permian), but along the Valley City fault trough erosion has not removed enough material to expose these rocks, and therefore outcrops of igneous intrusions should not be expected. Elongated domes or anticlines could be formed if the intruding magma enter the beds along persistent fissures rather than limited ones.

A beautiful example of a fault trough occurring in an anticlinal dome has been described by Shand.[2] Asmari Mountain in Western Persia is a simple anticlinal dome of Oligocene limestone, 16 miles long and 3 miles wide at the middle. The northwestern end plunges rather steeply and shows no unusual structures, but in the southeast end, where the axis dips 5° or 6° only, a trough ½ mile wide and 2½–3 miles in length has been formed. Beds of gypsum belonging to the Fars System (Miocene) have been faulted down into the mountain limestone. The gypsum beds outcrop all around the base of the mountain and are locally conformable to the Asmari limestone, although the higher members of the system overlap the lower.

The trough is bounded by two main faults having an average dip

[1] L. M. Gould, "The Rôle of Orogenic Stresses in Laccolithic Intrusions," *American Journal of Science*, Vol. XII (1926), pp. 119–29.

[2] S. J. Shand, "A Rift-Valley in Western Persia," *Quarterly Journal of the Geological Society*, Vol. LXXV (1920), pp. 245–50.

of 70°, but on the northeast side there are at least three other parallel or step faults that form smaller scarps within the valley. In passing northwest toward the crest of the mountain the faults gradually die out; toward the southeast, near the base of the mountain, they abut against a cross-fault that runs at right angles to the anticlinal axis. The maximum downthrow along the main faults ranges from 150 to 500 feet. Fault surfaces are smoothed and fluted. Their excellent preservation is attributed to the arid climate and to rapid removal of the gypsum by occasional rains. The fluting and striations indicate that the displacements were vertical.

A perennial stream flowing directly across the structure has cut a narrow canyon in the limestone and an open valley in the gypsum. A waterfall near the mouth of the canyon has receded some 60 feet from the fault where it started, thus proving that no recent displacement has occurred along this fault. The water flows into a fissure on the fault plane, leaving the stream bed dry for some distance below. A wet weather stream disappears in the same way on crossing one of the faults within the trough.

If the bounding faults continue downward without change in dip they would intersect at a depth of about 4,000 feet. While the faulting may extend to several times this depth, its superficial character is indicated by the relatively small displacement and the lack of persistence along the strike. The faults are merely incidental to the formation of the trough, and do not extend beyond it. The trough cannot be attributed to earthquakes originating along the faults, for the faults have been formed by the subsidence of the trough.

The valley now occupying the trough is a product of erosion, and, aside from the freshness of the inclosing scarps, it does not possess the characteristics of a tectonic valley. Therefore, as pointed out by Sir Jethro Teall and Mr. R. D. Oldham, it is hardly proper to call it a rift valley.

Anticlinal elevations similar to Asmari Mountain are found elsewhere in Southwest Persia. Richardson, in referring to the topography of the region, mentions the numerous intact arches of limestone forming "whale backs."[1]

[1] R. K. Richardson, "The Geology and Oil Measures of South-West Persia," *Jour. Institute of Petroleum Tech.*, Vol. X (1924), pp. 256–96.

Of similar origin are probably "the rift valleys" of eastern Sinai, described by Hume,[1] for his sections indicate that much erosion has taken place since the faulting occurred. The fault trough occupied by the Wadi Raib, he states, is "due to the breaking down of an anticlinal fold, the center having been step-faulted." Upper Nubian sandstone, and in one place also an overlying Cretaceous limestone, have been let down between granite gneiss capped with Lower Nubian. Beadnell found "typical rift valleys" in central Sinai similar to those described by Hume. He states that their structure is "impressed on the mind by their walls of granitic rock and floors of sandstone."[2]

The fault troughs associated with anticlines, domes, and monoclinal flexures are phenomena subordinate to the uplifts which have resulted in the flexing of the strata, and the faulting is clearly superficial. The development of such troughs would be accompanied by local earthquakes only, except in cases where the trough is located along a flexure which in depth passes into a profound fault in crystalline rocks. The rock masses involved in the formation of the troughs are too small, and the elasticity and rigidity of the material too low, to produce great earthquakes. The fault wedges could not force the inclosing rocks apart by their own weight, for they are small and there is little or no difference in density.

Lawson has suggested that the formation of a large fault trough by distension would bring about a deficiency in mass which would be compensated by the inflow of rock in depth, thus elevating the area embracing the trough and depressing the border areas on each side so as to produce a flat-topped arch.[3] The fault troughs here described are much smaller than those referred to by Lawson, and are, as previously stated, clearly subsidiary to the folds. In southern Utah fault troughs are present in some folds and absent in others. In the Farnham dome a horst has been formed instead of a fault trough.

[1] W. F. Hume, *The Rift Valleys and Geology of Eastern Sinai*, London, 1901. Pp. 49.

[2] H. J. L. Beadnell, "Central Sinai," *Geographical Journal*, Vol. LXVII (1926), p. 394.

[3] Andrew C. Lawson, "The Geological Implications of the Doctrine of Isostasy," *Bulletin of the National Research Council*, Vol. VIII (1924), pp. 15–17.

It is frequently suggested that fault troughs are formed by the collapse of an anticlinal arch. Rocks have insufficient strength to support their own weight as a large arch, and if the forces causing the uplift be discontinued the updomed beds would merely flatten out again, or, if that were impossible because of horizontal resistance, and rupture occurred, thrust faults would be formed rather than normal faults. But, wherever observed, the faults are normal and steeply inclined, and there is no crushing or crumpling of the rock strata such as would indicate strong compressive forces. The faults may even be open enough for water to run into them.

The only hypothesis which seems to fit the evidence is that this type of fault trough results from a local distension of the surface due to differential uplift. When horizontal beds are locally uplifted to form a dome or fold, the beds must either stretch or break. If the weight of overlying rock is sufficient the beds will stretch or flow under the differential pressure; but, if insufficient, fissures will tend to form. Deep open fissures are not likely to develop, however, especially in sedimentary strata of little tensile strength, for gravity would cause a wedge of rock to slip down and fill any opening as fast as it was formed. That the downfaulting has been coincident with the distension is indicated by the drag or upturning of beds along the sides of the wedge. The prevalence of erosion valleys along anticlinal axes, even where trough faulting has not occurred, is probably due to the presence of strike joints resulting from distension.

The writer is inclined to attribute the distension that results in trough faulting to a bulging up of the anticlines by strictly vertical forces, and he has given evidence that this is the explanation of the domes in southern Utah. This view is not incompatible with the hypothesis that the anticlines may have been formed by tangential compressive forces if they be conceived to have acted at considerable depth below the surface; on the other hand it is not necessary to postulate such forces.

Some fault troughs that do not occur in well-defined folds are probably also due to distension, though it may not be possible to prove it, especially where the rock strata have been greatly disturbed prior to the trough faulting.

Certain fault troughs associated with synclines, such as the one

near Ephrata, Pennsylvania, described by Stose,[1] may be due to distension, although it seems more likely that the blocks have been let down because of the withdrawal of support from below. The differential displacement of many small blocks suggest superficial rather than profound stresses, and the collapse may have resulted from intrusion and effusion of diabase near the close of the Triassic. In this and many other cases the evidence is insufficient for the drawing of definite conclusions.

TENSIONAL FAULT TROUGHS DUE TO ROTATIONAL STRAIN

Small tensional troughs may be formed as a result of rotational strain set up by unequal tangential compression. Moulton has advanced this as an explanation of the Fromberg fault trough south of Billings, Montana.[2]

The Fromberg fault extends for about 30 miles in a direction N. 40° E., and dips toward the northwest. It is paralleled on the northwest for 20 miles by another fault; and the strip between, having a width of from less than a mile to more than a mile and a half, has been dropped a maximum of 400 feet. Passing southwest the second fault is gradually replaced by a flexure. The rotational strain is attributed to compressional forces acting from the west which have brought about the upfolding of the Pryor and Bighorn mountains southeast of the faults, the movement decreasing toward the north. Moulton thinks that vertical forces may have aided in bringing about the uplift, but such forces, as pointed out previously, would also result in tension.

Fath has shown how belts of *en échelon* faulting in Oklahoma may be explained by postulating horizontal displacements along faults in the more competent underlying rocks which would set up rotational strain in the incompetent beds at the surface.[3] Similar but shorter fractures were formed in valley alluvium by the hori-

[1] George W. Stose, "New Type of Structure in the Appalachians," *Bulletin Geological Society of America*, Vol. XXXV (1924), pp. 469–71.

[2] Gail F. Moulton, "Faulting South of Billings, Montana," *Journal of Geology*, Vol. XXXII (1924), pp. 511–23.

[3] A. E Fath, "The Origin of the Faults, Anticlines, and Buried "Granite Ridge" of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geological Survey, Professional Paper 128* (1921), pp. 77–80.

zontal displacement along the buried San Andreas fault in 1906.[1] Under suitable conditions fault troughs would necessarily develop along normal faults formed in this way, but the writer knows of none.

TENSIONAL FAULT TROUGHS DUE TO TILTING OF FAULT BLOCKS

Subsidiary fault troughs commonly develop at the base of great scarps formed by normal faulting. They are often found near the inclosing scarps of large fault troughs. Because of their location they are rapidly filled with rock waste derived from the scarps and obliterated as physiographic features. Therefore they have been observed chiefly in arid regions or where recently formed. Some of these troughs are too large to be seismic in origin, although earthquakes may have aided in their development. The best explanation seems to be that they result from the tendency of crustal blocks to tilt away from troughs inclosed by normal faults. The way in which this occurs is discussed in more detail in connection with the origin of profound fault troughs (see p. 600).

PROFOUND FAULT TROUGHS

Large fault troughs range in width from perhaps 10 or 15 miles to 100 miles or more, but it is often difficult to determine their precise limits because of step faulting and downwarping near their margins.

The vertical displacement of the trough floors is measured in thousands of feet. The deepest lake basins have been formed by trough faulting: the floor of the Dead Sea trough is 2,600 feet below sea-level and over 5,000 feet below the highlands on each side; Tanganyika is 4,708 feet deep, the floor of the lake being 2,172 feet below sea-level, while the precipitous rocky cliffs that border it reach a height of over 4,000 feet above lake-level; Baikal, with a depth of over a mile, occupies a trough that has been formed directly athwart the course of the Selenga-Angara River, its bed being about 3,400 feet below sea-level. The Bartlett trough has a depth of 21,036 feet below sea-level.

[1] Stephen Taber, "Some Local Effects of the San Francisco Earthquake," *Journal of Geology*, Vol. XIV (1906), Figures 2 and 7.

Erosion and sedimentation have considerably modified all of the great fault-trough valleys, even the youngest. The high fault scarps inclosing the valleys are of slow growth, for they are the result of many small displacements. These valleys are deep because they are young, and most of them still have a relatively high seismicity.

In length the large fault troughs range up to several hundred miles. The longest known faults, or fault zones, are those associated with fault troughs. Suess, Gregory, and others have held that the trough faulting of East Africa and of Asia Minor is continuous and extends for over 60 degrees of latitude (4,000 miles). While this extreme view may be questioned, since the entire belt has not been studied in detail, the persistence of the faulting in several different sections for hundreds of miles is now clearly established. The Jordan-Akabah trough extends 400 miles from the Orontes Valley to the Red Sea. The Bartlett trough is nearly 1,000 miles in length. That the faulting extends to profound depths is indicated by the persistence of the faults, by the magnitude of the displacements, and by the prevalence of volcanic activity, gas vents, steam jets, and hot springs where the faulting is sufficiently recent. The major faults probably extend downward to a depth where stresses are adjusted by rock flowage rather than by fracture.

Large fault troughs occur along the crest of geanticlines or plateaus and also perhaps as fore-deeps along the front of great mountain scarps. Since the latter are commonly filled with sedimentary deposits, as in the case of the Indo-Gangetic trough, or are below sea-level, it is difficult to determine whether folding or faulting has been the more important in their formation, and therefore they will not be considered in the present discussion.

In studying the origin of fault troughs, physiographic characteristics are of great value, but unfortunately most of them are rapidly obliterated by erosion and by the accumulation of rock waste, except in arid regions or in submarine areas of slow sedimentation. The floors of the troughs are often flat over quite large areas, and rise and fall in a longitudinal direction instead of being graded like river valleys. Cross-faulting has been observed in places, but it is of minor importance. The valley floors are often cut by faults parallel to the inclosing scarps and these sometimes result in minor troughs, es-

pecially at the base of the scarps. Therefore the deepest points within a trough are commonly located close to the inclosing scarps instead of near the center, as is usual with valleys of erosion.

Theories attempting to explain the origin of large fault troughs may be divided into three classes: (1) those that attribute the faulting to compressive forces acting transverse to the troughs; (2) those postulating uplift of the areas on each side of a trough by vertical forces; and (3) those that explain the troughs by subsidence under the force of gravity either with or without tension.

Andreae,[1] in 1887, suggested that the Rhine *graben* had been formed by thrust faulting. He assumed that the main faults diverged with depth but were concealed by the collapse of overhanging scarps. The normal faults observed along the sides of the trough were therefore subordinate features resulting from the collapse. Similar views were expressed by Salomon,[2] who thought that horizontal pressure at right angles to the strike of the trough had forced downward the mass between the faults, and by Walther,[3] who thought that horizontal pressure had caused the sides of the trough to rise.

Wayland suggests that the Lake Albert fault trough has been formed by compressive forces, the main faults being buried under talus and masked by minor subsidiary blocks let down along normal faults. He recognizes that this mode of origin would necessitate enormous pressure.[4]

Willis has modified the compressional theory by suggesting that faults, which at the surface appear to converge downward, may curve backward so as to diverge in depth.[5] He thinks that the fault forming the east scarp of the Sierra Nevada curves back under "the mountain mass like a sole or bottom," and that many other faults which in the past have been regarded as normal are thrusts of this

[1] A. Andreae, "Eine theoretische Reflexion über die Richtung der Rheinthalspalte," *Verh. nat.-hist.-med. Ver. Heidelberg*, N. F., Bd. 4, 1887.

[2] W. Salomon, "Über die Stellung der Randspalten des Eberbacher- und des Rheinthalgrabens," *Zeitschr der Deutsch. Geol. Ges.*, Bd. 55 (1903), p. 412.

[3] J. Walther, *Zeitschr. der Deutsch. Geol. Ges.*, Bd. 66 (1914), Monatsbeiheft, Footnote, p. 304.

[4] E. J. Wayland, "Some Account of the Lake Albert Rift Valley," *Geographical Journal*, Vol. LVIII (1921), pp. 344–59.

[5] Bailey Willis, *Geologic Structures* (New York, 1923), p. 78.

type.[1] Such faulting would likewise subject the narrow block of a fault trough to enormous pressure, especially if the recurving fault surface flattens out in depth (see Fig. 4).

Evidence against the compression hypothesis may be briefly summarized:

1. Great fault troughs are commonly located near the summits of plateaus, and plateau structure is not characteristic of regions subjected to great compressive forces. Much evidence has been adduced in recent years in support of the view that plateaus are uplifted by vertical forces.

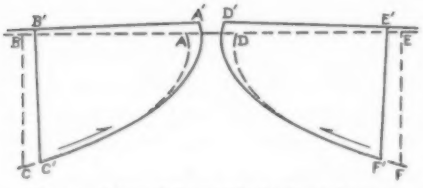

FIG. 4.—A trough formed by horizontal pressure, the faults diverging downward as suggested by Willis. The mass AD would be subjected to great compression.

2. The compressional hypothesis does not adequately explain the origin of two long parallel faults or fault zones.

3. It is incompatible with the flat floors that are characteristic of many fault troughs. The floor of the Lake Albert trough, as shown on Wayland's section, is flat. Moreover, as he states, crystalline rocks are exposed in the lower part of the scarps on both sides, while shales, much weaker rocks, have been encountered in the valley floor, and oil seepages, indicative of the presence of sedimentary rocks, occur in several places.[2] This structure is irreconcilable with enormous pressure. Sedimentation alone does not explain the flat floor, for the location of the divides close to the scarps denotes a youthful tectonic valley.

4. The structural displacements observed in the floor rocks of fault troughs are those that accompany normal faulting—not thrust faulting. Lake Baringo which lies near the eastern scarp of the Rift Valley of East Africa is tectonic in origin, being due to minor faulting and warping.[3] The north shore is formed of lava sheets broken

[1] Bailey Willis, "Earthquake Risk in California," *Bulletin Seismological Society of America*, Vol. XIV (1924), p. 24; also in *Geologic Structures* (1923), pp. 45–46.

[2] E. J. Wayland, *op. cit.*, p. 352.

[3] J. W. Gregory, *The Rift Valleys and Geology of East Africa* (London, 1921), pp. 107–11.

by faulting into a series of parallel troughs and horsts, the floors of the troughs and the tops of the horsts being flat, and the scarps nearly vertical.[1] Minor fault troughs seem to be a common accompaniment of large fault troughs, and they are frequently located in the major fault zones near the base of the inclosing scarps. Gregory states that the lakes Kibibi[2] (Solai), Miviruni,[3] Losuguta[4] (Hannington), and Magadi[5] occupy secondary rift valleys on the floor of the major rift valley.

5. The presence of depressions or minor troughs at the base of fault scarps is a characteristic of normal faulting, for the collapse of overhanging scarps resulting from thrust faulting would fill and obliterate such depressions if formed. Even sloping scarps are rapidly worn back by erosion, and therefore depressions at their base are filled with waste except where they have been formed very recently, or where the scarps have been protected from rapid erosion by an arid climate or by submergence below sea-level.

Lake Losuguta, which is long and narrow, lies on the east side of the Rift Valley at the foot of a precipice 1,900 feet high. For some hundreds of feet the cliff is absolutely vertical. The opposite shore is formed of a series of steps and terraces.[6]

The precipitous slopes of the trough between Santa Catalina and San Clemente Islands led Lawson[7] to suggest that it occupies a *graben*. The trough has a flat floor with average depth of 4,000 feet below sea-level. Its general form is clearly shown on the bathymetric chart of the California Coast south of San Francisco,[8] but the contour interval of 100 fathoms is too large to disclose minor depressions. The soundings on which the contours outlining the trough are based were obtained from the Hydrographic Office, and these figures positively establish the presence of depressions near the base of the main inclosing scarps (see Figs. 5 and 6.)

[1] J. W. Gregory, *The Great Rift Valley* (London, 1896), p. 132.

[2] *Ibid.*, p. 308. [3] *Ibid.*, p. 314. [4] *Ibid.*, p. 314.

[5] J. W. Gregory, *The Rift Valleys and Geology of East Africa* (London, 1921), p. 174.

[6] J. W. Gregory, *The Great Rift Valley* (London, 1896), p. 110.

[7] Andrew C. Lawson, "The Continental Shelf off the Coast of California," *Bulletin National Research Council*, Vol. VIII, Part II, No. 44 (1924), p. 10.

[8] Bathymetric Chart, San Francisco to Point Descanso, Hydrographic Office, U.S. Navy No. 5194 (March, 1923).

The location of long narrow subsidiary troughs near the base of the scarps inclosing the great Bartlett trough has been referred to in several previous papers.[1]

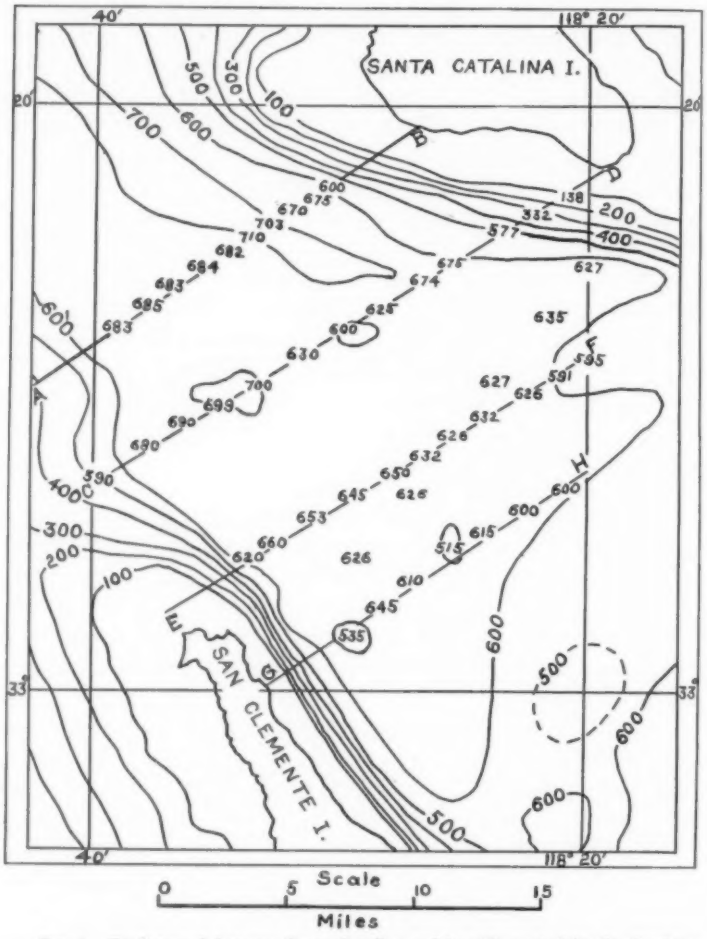

FIG. 5.—Fault trough between Santa Catalina and San Clemente Islands. Contour interval 100 fathoms (600 feet). Based on sonic soundings furnished by the Hydrographic Office of the U. S. Navy.

[1] Stephen Taber, "The Great Fault Troughs of the Antilles," *Journal of Geology*, Vol. XXX (1922), pp. 92, 96–97, and 99.

The depressions found at the base of some scarps are due to recent faulting, accompanied by tilting of the valley floor. Dixey suggests this as an explanation of the location of the Shire River, which flows close to the eastern fault scarps wherever they are high and well defined, although wide valley plains extend away toward the west.[1] Accumulation of rock waste at the base of the scarps will tend

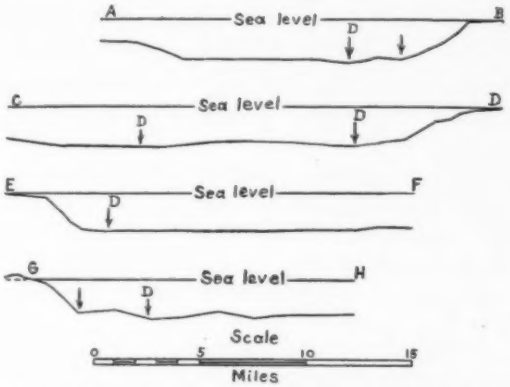

FIG. 6.—Profiles across fault trough between Santa Catalina and San Clemente Islands. Based on sonic soundings furnished by the Hydrographic Office of the U.S. Navy. Vertical scale is twice the horizontal scale. Arrows indicate depressions, and "D" the deepest soundings.

to push the river gradually westward toward the center of the valley; its location at the base of the scarp is indicative of recent faulting.

6. The faults inclosing great tectonic troughs are associated with, and in some instances pass into, monoclinal flexures. They are not associated with closely folded and overturned anticlines or other structures indicative of compression. The geologic sections of Lartet[2] and Blanckenhorn[3] show that the western slope of the Dead Sea trough has been formed partly by downwarping of the strata and partly by faulting.

[1] F. Dixey, "The Nyasaland Section of the Great Rift Valley," *Geographical Journal*, Vol. LXVIII (1926), p. 128.

[2] Louis Lartet, *Exploration Géologique de la Mer Morte de la Palestine et de l'Idumée* (Paris, 1877).

[3] Max Blanckenhorn, "Entstehung und Geschichte des Todten Meeres," *Zeitschrift des Deutschen Palästina -Vereins*, Vol. XIX (1896).

The Port Nicholson depression at Wellington, New Zealand, lies between a fault scarp on one side and a flexure on the other. Cotton states that the faulting must be regarded as merely an incident to the formation of the depression which has been brought about by the sharp downwarping of a belt over 30 miles in length and at least 10 miles wide, the vertical displacement amounting to 1,500 feet or more.[1]

The Vale of Eden in Northern England and the Triassic trough in the Connecticut Valley have been interpreted as asymmetrical troughs formed in this way,[2] and the Unkar wedge exposed in the Grand Canyon of the Colorado[3] is probably a remnant of a similar structural feature.

7. While several writers have assumed that the faults inclosing the troughs are divergent, a careful search through many descriptions of fault troughs has failed to disclose any record of this structure having been observed, even in old troughs that have been subjected to much erosion, whereas normal faults inclosing troughs have been described repeatedly.

The hypothesis that fault troughs are formed by uplift of the areas on each side rather than by subsidence of narrow blocks is usually associated with the conception of divergent faults and compressive forces, but it is conceivable that the forces may act vertically, though no evidence has been adduced in support of it. Some of the deepest troughs are below sea-level and yet have never been connected with the sea. The rocks on each side of the Tanganyika trough are older than the valley or are continental in origin. Collie states that in East Africa the original plateau surface was apparently highest in the vicinity of the present rift valley, as the lavas have flowed both ways from it.[4] Evidence that the great Antillian troughs are due chiefly to subsidence has been given in earlier papers.

[1] C. A. Cotton, "The Geomorphology of Wellington," *New Zealand Nature Notes*, Wellington (1922), pp. 1–8.

[2] W. G. Foye, "Origin of the Triassic Trough of Connecticut," *Journal of Geology*, Vol. XXX (1922), pp. 690–99.

[3] L. P. Noble, *op. cit.*, Plate I, Sections B–B′ and C–C′.

[4] G. L. Collie, "Plateau of British East Africa," *Bulletin Geological Society of America*, Vol. XXIII (1912), p. 303.

If the troughs have not been formed by thrust faulting or by uplift of the inclosing areas they must be due to gravity.

A century ago Eli de Beaumont compared the Rhine Valley trough to the fallen keystone of an arch, the abutments of which remained standing. In recent years Dr. J. W. Gregory has been the leading supporter of the keystone theory, applying it to the great trough valleys of East Africa. Most geologists who have adopted this theory have assumed that the arch was compressional in origin and not due to vertical forces. The objections to this view already have been given. Other geologists have attributed the troughs to tension. This theory has been advocated recently by Krenkel[1] with reference to the troughs of East Africa, though he opposes the "anticlinal hypothesis" of Gregory. Weber[2] thinks that the tension has resulted from compressive stresses acting in a direction parallel to the axis of the trough, and cites the development of mountain folds transverse to the strike of the fault troughs in Europe and Africa; but in America the folding has been parallel to some of the troughs. He argues that if the arch were formed by a centrifugal force of deep origin, then this force, unless hindered in some unexplained way, would prevent the dropping of keystones as well as abutments.

The formation of an arch is a prerequisite to trough faulting under the influence of gravity only where the arching is due to vertical forces, and therefore results in distension. No arch is necessary if the tension be brought about in some other way.

Lawson's hypothesis, that the formation of a trough causes a deficiency in mass which is compensated by inflow from a zone on each side, thus producing uplift of the area, has been mentioned (p. 588). He thinks this would be true whether the dropped block be "a wedge between down-converging walls confined to the superficial crust, or . . . . a prism traversing the entire crust to the zone of compensation."[3] Evidence indicates that the major faults involved in the formation of large fault troughs extend to profound depths instead of being confined to the superficial crust, and a prismatic block in-

[1] E. Krenkel, *Die Bruchzonen Ostafrikas* (Berlin: Gebr. Borntraeger, 1922).

[2] Maximilian Weber, *op. cit.*, pp. 257–60.

[3] A. C. Lawson, "The Geological Implications of the Doctrine of Isostasy," *Bulletin of the National Research Council*, Vol. VIII, Part IV, No. 46 (1924), p. 16.

closed between parallel fractures that reach the zone of compensation would not tend to sink unless there be an increase in the density of the material of which it is composed or a withdrawal of material from under it.

It is conceivable for gravity to bring about the subsidence of large fault blocks in any one of three ways: (1) by tension, or, rather, reduction of horizontal pressure so as to permit a wedge-shaped block to subside; (2) by withdrawal of material from under the block; and (3) by a change in the density of subsurface material. The evidence bearing on these three hypotheses will be briefly discussed. It is rather meager and somewhat conflicting. More than one factor has probably entered into the formation of some of the larger and more complex troughs, and they seem to have had a longer history than was once thought probable.

1. If a region is subjected to tension, normal faults are formed; and a wedge inclosed between downward converging faults would tend to sink because the pressure per unit area is greater at the base of the wedge than under the adjoining blocks. The downward pressure is at a minimum under the edge of the inclosing blocks, which therefore tend to tilt away from the wedge. These displacements may be illustrated with wooden blocks that float in water, although the fluid is not strictly analogous to rocks, even in the zone of flow (see Fig. 7). Fissures that widen upward toward the surface are formed between the wooden blocks; but similar yawning fissures could not develop in the earth's crust, for a subordinate wedge of rock would slip down and fill any opening as fast as formed. This hypothesis satisfactorily explains some of the characteristic physiographic features associated with large troughs, such as the subsidiary troughs at the base of inclosing scarps. Some of these subsidiary troughs are too large to be seismic in origin and they are probably best explained by tension.

If horizontal tension develops transverse to a single profound fault that is not vertical, the foot-wall side will tend to rise and the opposite side to sink, because of difference in pressure on opposite sides of the fault at the base of the crustal blocks, thus giving rise to an asymmetric trough bounded by a fault on one side and a flexure on the other. As the subsidence continues the rocks will tend to frac-

ture along the flexure with the development of step faulting. The Nyasan trough, as pointed out by Gregory[1] and by Dixey[2] is asymmetric, the eastern side being formed by one main fault with displacement of as much as 8,000 feet, while the western part of the downthrown block has been dropped in steps by parallel faults with the steps sloping to the east. The Port Nicholson depression, the Connecticut Valley trough, and other illustrations of asymmetric troughs have been given previously.

If horizontal tension develops transverse to a profound vertical fault, gravity would prevent the opening of a fissure by causing wedges to slip downward with the formation of normal faults dipping toward the vertical fracture from one or both sides.

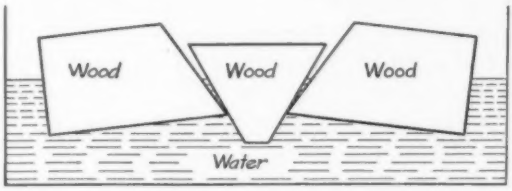

FIG. 7.—Wooden blocks floating in water

The tensile stresses producing trough faulting are probably local and result from differential uplift or subsidence due to change in density or the movement of deep-seated magmas, for the rocks are too weak to transmit such stresses any appreciable distance. More accurately stated, the rocks at depth are not subjected to tension but to reduction of the normal horizontal pressure.

2. Calderas are formed by collapse following the ejection of large quantities of volcanic materials from a central vent. Similarly, troughs are possibly formed by collapse following the extrusion of material along fissures. Extensive volcanic activity has preceded or accompanied the formation of some large fault troughs, but it has been of little or no importance in the formation of others.

The structural characteristics of the rift valley near Nairobi in Kenya Colony, where volcanism has been important, are quite dif-

[1] J. W. Gregory, *The Rift Valleys and Geology of East Africa* (London, 1921), p. 305.

[2] F. Dixey, *op. cit.*, p. 120.

ferent from those of most of the major troughs in the African rift valley system, which are located in districts where volcanism has been absent or unimportant. This difference has been noted by Sikes, who states that near Nairobi the trough is characterized by numerous parallel fault-block ridges and valleys, the limits of the trough being indefinite, as it is not bounded by high, steep fault scarps.[1] By contrast the Nyasa, Tanganyika, Albert, and Edward troughs are flat-floored depressions confined between well-defined boundary walls.

Sikes distinguishes several periods of volcanism and finds evidence that at many places periods of intense volcanism on the flanks of the rift valley were followed by periods of subsidence of the regions comprising the vents.[2]

It seems probable that volcanism has been a contributing factor in the formation of fault troughs, though it is doubtful if any of the major troughs can be attributed solely to this process.

3. Increase in density of underlying material would result in the formation of a fault trough only if the change be limited to a narrow zone. Theories as to the causes of such a change are at present rather speculative, but crystallization of magma and expulsion of gases are probably among the more important. Change in density might be limited to a narrow zone if brought about by faulting or possibly by folding. Hot springs are common along profound faults, such as those associated with large fault troughs. Noble states that the pre-Tertiary rocks along the Garlock fault in southern California are profoundly altered, apparently by hydrothermal agencies, over a zone as much as a mile in width. A trough has been formed along part of this fault.[3]

The crystallization of a typical basalt is accompanied by a contraction in volume of about 11 per cent.[4] If this change in state take

[1] H. L. Sikes, "The Structure of the Eastern Flank of the Rift Valley near Nairobi," *Geographical Journal*, Vol. LXVIII (1926), p. 390.

[2] Sikes, *op. cit.*, p. 393.

[3] L. F. Noble, "The San Andreas Rift and Some Other Active Faults in the Desert Region of Southeastern California" (Report of the Advisory Committee in Seismology), *Carnegie Institution Yearbook No. 25* (1925–26), pp. 423–25.

[4] A. L. Day, R. B. Sosman, and J. C. Hostetter, "The Determination of Mineral and Rock Densities at High Temperatures," *American Journal of Science*, Vol. XXXVII (1914), pp. 25–33.

place along a narrow zone as a result of faulting, or other cause, a trough might be produced.

Accurate gravity surveys of the larger fault troughs would possibly shed some light on their origin, but as yet few data are available. Kohlschütter's gravity observations along east-west lines across the rift valleys of Africa led him to conclude that, while the elevation as a whole is fully compensated, the boundary scarps show an excess of mass and the valley floors are about normal or show a slight deficit.[1] The conclusion that the troughs are uncompensated is supported by A. Born and other German investigators, some of whom attribute the troughs to tension, while others attribute them to compression.

On the basis of computations of German data made by Dr. William Bowie, Lawson states that "today the gravity anomalies in the *graben* of the Rhine are small and average zero."[2]

Some fault troughs have been obliterated as physiographic features by erosion and deposition without renewal of faulting. The Limagne fault trough in Southern France seems to have had its valley filled with sediments which have later been removed by erosion so as to again expose the inclosing scarps;[3] and all this has taken place without noticeable renewal of faulting.

While some of the fault troughs previously described may be uncompensated, it is more doubtful whether this would be true for one as large as the Bartlett trough, even though the major faults converge downward.

If a depression were formed by either the withdrawal of underlying material or an increase in density, there would be a tendency for the surface to sag before faulting occurred. Monoclinal flexures would develop in the less rigid rocks and the flexing might be followed or accompanied by faulting, especially step-faulting. The strata within the fault blocks would tend to dip toward the trough, the boundaries of which would seldom be sharply defined.

The great tectonic valley in the southern Namib, Southwest Africa, has been formed, according to Beetz, by the subsidence of a

[1] E. Kohlschütter, "Ueber den Bau der Erdkrust in Deutsch-Ostafrika," *Nachrichten Ges. Wiss. zu Göttingen, Math-phys. Kl.* (1911), pp. 1–40.

[2] A. C. Lawson, *op. cit.*, p. 16.

[3] W. M. Davis, "The African Rift Valleys," *Science*, N. S., Vol. LII (1920), p. 458.

relatively narrow strip between two monoclinal flexures.[1] It is difficult to explain why subsidence should be limited to a narrow strip unless there was preliminary faulting which permitted escape of lava or gases, or initiated other changes in the condition of the material in depth; but inability to explain does not mean that it has not occurred. Possibly the monoclines are merely the superficial effects of normal faulting in more rigid underlying rock. A detailed survey of the area is highly desirable.

The presence of a profound fault seems to be almost a prerequisite for the development of a large trough as a result of extrusion, crystallization, or other igneous processes; and, even where igneous activity has been absent, the formation of such faults has, in some cases at least, apparently preceded the development of the troughs, for some troughs cut across earlier structures in such a manner that the initial formation of the faults cannot be attributed to tension.

Dixey states that in the Nyassaland section "the Rift Valley faults have cut right across the foliation of the crystalline rocks as well as the boundary faults of the Karroo series," but because of the absence of thrusts, folds, and other evidences of compression he concludes that the trough is due to regional tension.[2]

Wayland has pointed out that the Lake Albert trough cuts directly across the structure of the country without reference to earlier faults or other lines of tensile weakness.[3] He thinks this is evidence that the trough has been formed by thrust faulting; but the displacements described by him and indicated on his map suggest that the early faults may have been offset by horizontal movements along later faults, and that the trough has developed by subsequent subsidence of blocks along the later faults and locally along the older ones so as to give the staggered arrangement of the scarps.

Displacements parallel to the strike of faults are difficult to recognize and therefore their importance has been generally overlooked. Evidence has been given that the San Andreas fault in California originated through shearing in a horizontal direction, and a similar origin has been suggested for some of the parallel faults, such as the

[1] Werner Beetz, "On a Great Trough-Valley in the Namib" (translated by P. A. Wagner), *Transactions of the Geological Society of South Africa*, Vol. XXVII (1924), pp. 1–38.

[2] F. Dixey, *op. cit.*, pp. 119, 135. [3] E. J. Wayland, *op. cit.*, pp. 352–54.

Haywards fault.[1] Additional evidence of the prevalence of horizontal displacements along these faults has since been published by Vickery,[2] Russell,[3] Davis,[4] and Noble.[5] Similar displacements amounting to about 12 miles are thought to have occurred along the Osburn fault, which extends for 300 miles in Washington, Idaho, and Montana.[6]

The system of more or less parallel and branching faults to which the San Andreas fault belongs is comparable in its persistence to the fault systems of East Africa and Palestine, but in most other respects it differs greatly. While seismic fault troughs are common along the San Andreas fault, troughs comparable in size with those of East Africa are not found north of Salton Basin. This may be due to the absence of volcanic activity and the prevalence of compression rather than tension in the region traversed by the fault. Hot springs are the only evidence of igneous activity along the fault; and instead of crossing a plateau, it passes through a mountain region characterized by folding and thrust faulting.

Near the head of the depression occupied by the Gulf of California and Salton Basin the fault system apparently enters a different tectonic province. The depression is clearly diastrophic in origin. Salton Basin is outlined by faults and others are probably buried under the delta deposits of the Colorado River. Brown[7] states that most of the faults in this district are of the normal type. Solfataras or mud volcanoes and recent igneous extrusives are found near the center of the trough. Darton[8] has shown that much of the peninsula

[1] Stephen Taber, "Some Criteria Used in Recognizing Active Faults," *Bulletin of the Geological Society of America*, Vol. XXXIV (1923), pp. 664–66.

[2] F. P. Vickery, "The Structural Dynamics of the Livermore Region," *Journal of Geology*, Vol. XXXIII (1925), pp. 612–13.

[3] R. J. Russell, "Recent Horizontal Offsets along the Haywards Fault," *Journal of Geology*, Vol. XXXIV (1926), pp. 507–11.

[4] W. M. Davis, "The Rifts of Southern California," *American Journal of Science*, Vol. XIII (1927), p. 64.

[5] L. F. Noble, *op. cit.*, p. 417.

[6] J. B. Umpleby, "The Osburn Fault, Idaho," *Journal of Geology*, Vol. XXXII (1924), pp. 601–3.

[7] J. S. Brown, "Fault Features of Salton Basin, California," *Journal of Geology*, Vol. XXX (1922), p. 226.

[8] N. H. Darton, "Geologic Reconnaissance in Baja California," *Journal of Geology*, Vol. XXIX (1921), p. 747 and Figs. 3 and 4.

of Baja California has been lifted above sea-level in very recent geologic times. Tertiary sedimentaries with interbedded tuffs and sheets of basalt dip gently toward the west but are cut off abruptly near the east side of the peninsula. The structure of this region, therefore, more closely resembles that of East Africa and Palestine.

Under the Taylor-Wegener hypothesis of drifting continents, mountains are supposed to be formed along the borders of advancing land masses where resistance to movement crumples up the rock strata. Tensional effects, such as fault troughs, would be expected to develop near the rear margins of the moving land areas, but nothing of this sort seems to have occurred. Fault troughs are found on both sides of North America, and in both instances they differ in age from the mountain ranges on the opposite side.

It is obvious that more detailed investigations of the profound fault troughs are needed before it will be possible to draw definite conclusions as to their origin. The largest troughs are of the same order of magnitude as mountain ranges, yet their origin has attracted little attention as compared with that of mountains.

Of all the great troughs, the Bartlett trough probably offers the best opportunity for research. It lies between two zones of active faulting, and the sea waves that accompany most of the great earthquakes indicate that the displacements are dominantly vertical. Both fault zones continue eastward beyond the trough, crossing the Island of Haiti; and recently Mr. Ower has found two important faults in Central America that appear to be in continuation of the southern and northern walls of the trough.[1] Islands located near the tops of the boundary scarps are available for gravity stations and other precise observations: on the north, Cuba and the Cayman Islands, on the south, the Bay Islands, Swan Island, Jamaica, Navassa Island, and the southern peninsula of Haiti. Since sedimentation is slow, the tectonic topography should be preserved with slight modification, and, through use of the sonic depth finder, it could be easily and accurately mapped. A complete investigation would necessitate the co-operation of the geodesist, geologist, seismologist, and oceanographer.

[1] Mentioned by Dr. J. W. Evans in his discussion of the paper by C. A. Matley, "The Geology of the Cayman Islands (British West Indies)," *Quarterly Journal Geological Society*, Vol. LXXXII (1926), p. 387.

TRIASSIC-JURASSIC "RED BEDS" OF THE ROCKY MOUNTAIN REGION

E. B. BRANSON
University of Missouri

ABSTRACT

A correlation table and distribution map of the Jurassic and Triassic red formations of the Rocky Mountains and adjacent regions furnishes background for discussion of correlation and origin of the "red beds." No worth-while basis for the separation of the upper red beds from the lower was found. Vertebrate fossils occur in several members, but are of little value in correlation. Various characteristics indicate marine origin for the major part of the red beds and subaerial origin for other parts. The discussion is confined to the red formations investigated by the writer, and conclusions concerning origin apply only to those formations.

INTRODUCTION

In some of the literature of recent years concerning the "red beds" of the Rocky Mountain region, postulates of earlier writers have been assumed to be facts, and local characteristics of some of the members of the red formations have been considered as common to the greater part, by writers who have not had extensive field experience on the Rocky Mountain red beds. It therefore seems worth while to summarize many of the main facts concerning the red beds and to list reasons for various conclusions.

The writer's investigations of the red beds have extended over eleven summers. During all but two summers the red beds were not the main object of investigation, but they were ever a subject of study. His studies have extended from the northern limit of the red formations in Montana to the southern in Arizona, and from the eastern limit in Colorado to near the western in Utah (Figs. 1 and 2). On account of the large area involved, detailed studies have been possible in only a small part of the red formations.

The discussion in this paper is limited in the main to the correlation and origin of the red beds above the Permian of the Rocky Mountain and adjacent areas. The Permian is not included because the writer's studies of its formations have not been extensive, and the Dockum of Texas and New Mexico and the Dolores of Colorado

are touched lightly for the same reason. The correlation has been summarized in several papers of the last decade, and the uncertain-

Fig. 1.—Outcrops of Triassic and Jurassic red beds of the Rocky Mountain region. Some outcrops in southwestern Nevada omitted.

ties have been emphasized. The origin has been discussed in many papers, and nearly all of those of recent date have concluded that it was continental. The writer does not attempt to discuss the origin

of red beds in general. They may be continental, marine, or a combination of the two. The origin of the color of red sediments is not considered in this paper.

DISTRIBUTION OF RED-BED FORMATIONS

The appended table (Fig. 3) lists nearly all of the formations that have been included in the post-Permian red beds of the area under discussion.

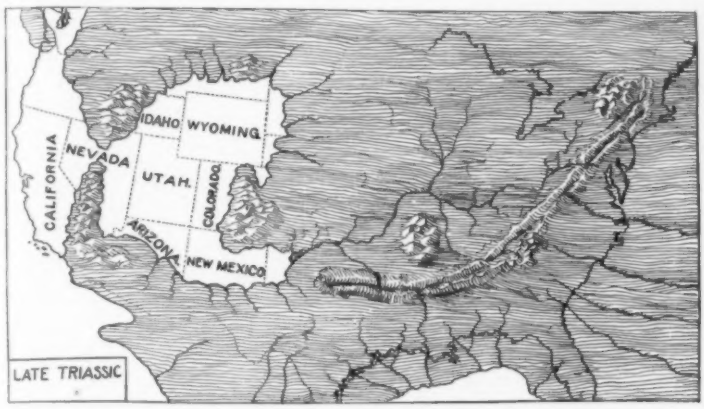

Fig. 2.—Paleographic map of an upper Triassic sea with a large river emptying into it from the East.

On the east slope of the Front Ranges in Colorado the red bed series is made up of the Fountain, Lyons, and Lykins. The Fountain and Lyons are Pennsylvanian in age, and the Lykins has been referred to the Permian in all literature of the last ten years. As shown on the geologic map of Colorado,[1] the Lykins runs to the Colorado line on the north, while the geologic map of Wyoming[2] shows the Chugwater on the Wyoming side taking the place of the Lykins on the Colorado side. That is, the Colorado state map shows all of the red beds at the Colorado-Wyoming line as Lykins, while the Wyoming map shows all of the red beds that join the Lykins on the Wyoming side as Chugwater. Either Lykins is equivalent to Chugwater,

[1] R. D. George, "Geologic Map of Colorado" (1913).

[2] M. R. Campbell and Others, "Geologic Map of Wyoming" (1925).

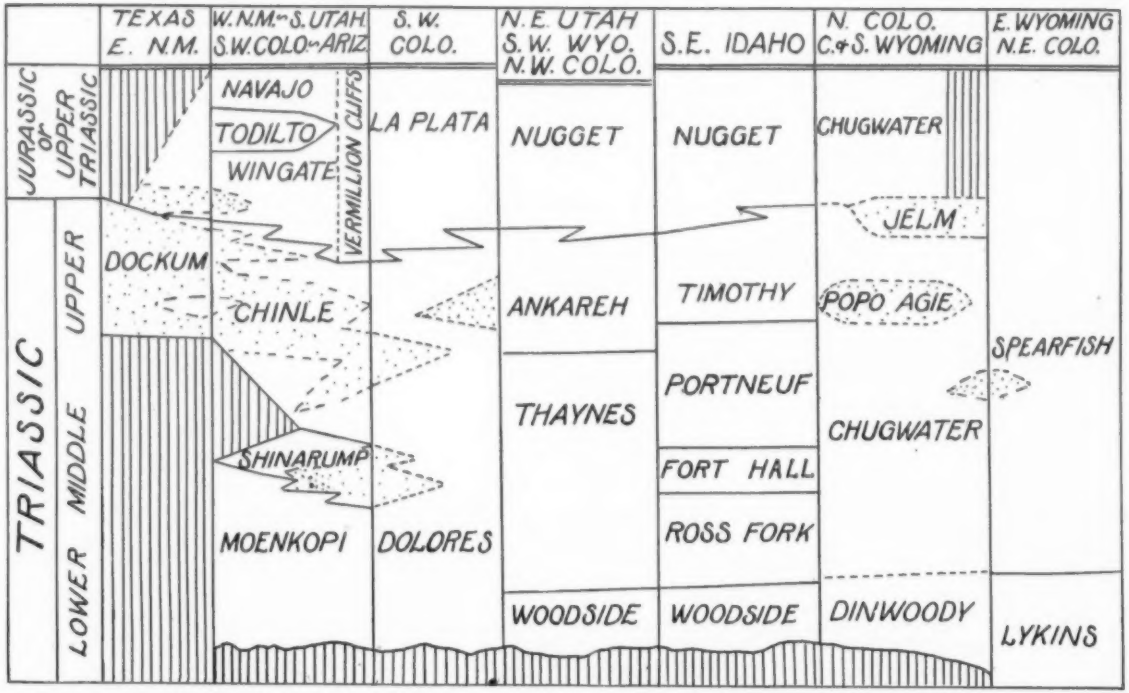

FIG. 3.—Generalized correlation table of Triassic and Jurassic "red reds" of the Rocky Mountain region. (1) Vertical lining indicates absence of that part in the section. (2) Dashed lines with dotted areas indicate continental members in marine. (3) No attempt is made to indicate thickness of strata. (4) Western Texas probably has formations equivalent to part of Wingate, Todilto, and Navajo, indicated by the blank space opposite those formations. (5) Part of northern Colorado and southern Wyoming have no formations equivalent to Upper Chugwater, indicated by vertical lining.

or the Permian Lykins thins northward and plays out so as to be unrecognizable in southern Wyoming, while the Triassic Chugwater begins as an unrecognizable unit in northern Colorado and thickens northward. Consequently, the bottom of the Chugwater is Permian at the Colorado-Wyoming line and the top of the Lykins is Triassic.

Northwestward from the Colorado line numerous outcrops of Chugwater appear. From Blackwelder's[1] description of the Laramie-Sherman area one concludes that the Chugwater may include upper Permian, all of the Triassic and, possibly, some Jurassic, though Blackwelder did not state such a conclusion. However, the correlations are not based on paleontologic evidence. Knight[2] refers only the upper 250 feet of the Chugwater to the Triassic on the basis of vertebrate fossils found in one member, the Jelm, 250 feet below the top. As these fossils are Upper Triassic in age and the unconformity below the Jelm is local, the basis for drawing the Paleozoic line at that place seems inadequate. The present writer suggests that the part of the Chugwater above the vertebrate-bearing members be correlated with the La Plata to bring the correlation of the beds east of the Front Ranges in harmony with those west.

Northward from the Colorado line east of the Front Range, the Chugwater, which includes all of the red beds, thickens by addition of new sandstone members until on the west slope of the Big Horn Mountains it includes all of the Permian that is present and all of the Triassic.[3] Westward from the Big Horn region the lower part changes gradually to non-red limestones and shales until in the Wind River region the Phosphoria and Dinwoody formations, the former mainly limestone some 400 feet thick, the latter mainly shales and limestones about 200 feet thick, are distinct from the red beds. (The relationships in the Big Horns are taken from Condit. The writer has not examined the sections on the west slope of the Big Horn Mountains.) Southeastward from the Wind River Mountains, red beds outcrop in several places. They are more than 1,700 feet thick and well exposed near the Lost Soldier oil field, about 50 miles south-

[1] *U. S. Geol. Survey, Folio 173.*

[2] S. H. Knight, "Age and Origin of the Red Beds of Southeastern Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), p. 168.

[3] D. Dale Condit, "Relations of the Embar and Chugwater Formations in Central Wyoming," *U.S. Geol. Surv., Prof. Paper 98* (1916), p. 264.

indicated by the blank space opposite those formations. (5) Part of northern Colorado and southern Wyoming have no formations equivalent to Upper Chugwater, indicated by vertical lining.

east of the Wind River Mountain exposures.[1] The lower 350 feet, which consist of alternating limestone and shale, are probably equivalent to the Phosphoria and Dinwoody, though they have not yielded fossils by which they may be correlated and the lithology is decidedly different. The succession is similar to that on the west slope of the Big Horn Mountains, but the thickness is greater.

Chugwater, similar to that at Lost Soldier, is well exposed near Rawlins, 30 miles south of Lost Soldier, but has not been studied in detail. Fifty miles south of Rawlins, on Battle Creek near the Colorado line, Chugwater rests directly on granite, and the lower, partly limestone phases are absent, though they are well represented at the Colorado-Wyoming line 60 miles east, the locality considered first in this paper. Only the upper part of the formation is represented.

Seventy miles southwest of the Battle Creek outcrops, at the east end of the Uinta Mountains, the section which includes the red beds was described by Sears as follows:

Jurassic	Twin Creek limestone	(Sundance) limestone and shale	125′
	Nugget sandstone	White and gray cross-bedded sandstone. Some red sandy shale in the upper part	950′
Triassic	Ankereh shale	Red and gray sandy shale: sandstone and grit	200′
	Unconformity		
	Thaynes formation and Woodside shale	Mostly gray and drab shale; beds of limestone and sandstone	760′
Permian	Park City formation	White and gray limestone; chert; sandstone and shale; phosphate beds	115′*

* Julian D. Sears "Geology and Oil and Gas Prospects of Part of Moffatt County, Colorado, and Southern Sweetwater County, Wyoming," *Bull. U.S. Geol. Survey, 751*, p. 277.

This section is about 100 miles south of the Wind River exposures and is strikingly similar in lithology. The marine Twin Creek overlies the red beds as the marine Sundance overlies them in the Wind River Mountains. The Park City lies below them as in the Wind

[1] A. E. Fath, "Oil and Gas Fields of the Lost Soldier-Ferris District, Wyoming," *U.S. Geol. Survey, Bull. 756* (1924), pp. 14–15.

River Mountains. No fossils have been found in the Nugget to indicate its Jurassic age.

The present writer's examination of the exposures led him to correlate the formations described by Sears as follows: Twin Creek equals Sundance; Nugget, Ankereh, and Thaynes equal Chugwater; Woodside equals Dinwoody. The Sundance is correlated on the basis of fossils, while the other correlations are on the basis of lithology and relationships. Red-bed correlation is difficult, and the investigator often faces the problem of correlating with nearby regions in which the formations have been given different names on insufficient data, and he is unable to give correct relationships without investigating all of the regions concerned. It seems highly improbable that the red beds at the east end of the Uinta Mountains are nearly all Jurassic, while 100 miles east they are partly Permian and mostly Triassic, though their relationships and lithology are almost identical. Sears's correlation is with the Idaho section, and the Idaho correlation was made with western Colorado and Utah rather than with Wyoming formations. The attempt in this paper is to harmonize all of the correlations.

Southward from the Battle Creek outcrops, red beds outcrop intermittently along the west slope of the Park Range, but they have not been studied in detail. In the Aspen district, about 120 miles south of Battle Creek, red beds, called the Maroon and Triassic, range up to 6,600 feet in thickness. The upper 2,600 feet of this seems to correspond to the Chugwater, though there appears to be no sound reason for not including some of the Maroon with the higher beds in the Triassic series. In the Anthracite and Crested Butte region, a few miles south of Aspen, red beds are well developed. They were called the Maroon and Gunnison series by Eldridge.[1] The descriptions are too meager to furnish reliable data for the present study, and the writer has not visited the district.

About 40 miles southwest of the Anthracite and Crested Butte area is the Ouray region. This is the north part of a large area that has been mapped in detail in seven folios of the United States Geological Survey. In the folios' area are the type localities for the La Plata sandstone and the Dolores formation. The La Plata is wide-

[1] George H. Eldridge, *U.S. Geol. Survey, Anthracite and Crested Butte Folio*, p. 6.

spread in western Colorado. Along the Colorado River it outcrops continuously from near Delta, Colorado, to southern Utah. In southern Utah it is known as Wingate, Todilto, and Navajo. Outcrops, identified as La Plata, may be followed almost continuously from the type La Plata region northwest to the Battle Creek region at the Wyoming line. It seems to be possible to trace the La Plata to the top of the Chugwater on the north and to the Wingate, Todilto, and Navajo on the south. The southern Utah Wingate, Todilto, and Navajo may be followed almost continuously to the Santa Fe Railroad near Gallup, New Mexico, and westward to near Holbrook, Arizona.

FOSSILS AND CORRELATION

Correlating strictly on lithology and continuity of beds, the top of the Chugwater above the Popo Agie beds in central Wyoming, the part above the fossil beds, or Jelm, of southern Wyoming, much of the Nugget of southwestern Wyoming, Idaho, northeastern Utah, and northwestern Colodaro, the La Plata of central and southwestern Colorado, the Wingate, Todilto, and Navajo of southern Utah, Arizona, and New Mexico are of about the same age. These formations have been referred to the Jurassic without fossil evidence, but there is a tendency to reconsider the correlation of the Wingate, and all of the others should be considered with it.

Reeside says that W. T. Lee has adduced abundant evidence to show that the Sundance formation of Wyoming, as usually defined, contains in the lower part the equivalent of the Nugget sandstone of the Green River region. Only paleontologic evidence could warrant such conclusions, but it is entirely possible that the Upper Nugget is equivalent to the Lower Sundance, though most of the Nugget should be correlated with the Upper Chugwater.

The Dolores of Colorado, the Chinle of New Mexico, Arizona, and Utah, and the Chugwater of Wyoming have been correlated on the basis of land vertebrates. In the Chugwater of the Wind River Mountains the vertebrates occur in the Popo Agie member through 30–40 feet of rock. The member is 800 feet above the base and 600 feet below the top. So far as known to the writer, no bone has been found in any other part of the Chugwater of that region. The Popo Agie represents peculiar conditions, outlined in another paragraph,

and was the only time when land forms had opportunity to be preserved. It is practically certain that the land animals were present during the entire time while the Chugwater was being deposited, for they are known in considerable numbers from the Permian of Texas and from the Popo Agie. They did not migrate to the region for Popo Agie time only. The filling of the shallow sea in Popo Agie time and creation of landward sides of deltas gave the opportunity for the preservation of land vertebrates. Land vertebrates[1] have been found in the Chugwater of southern Wyoming 100 feet from the top. They are phytosaurs and amphibians as in the Popo Agie beds, but the same species have not been identified in the two places, and it seems improbable that the two were contemporaneous. The southern place may have been older or younger. It was merely another place where a delta built to the water level and above and the land forms could be preserved.

In the Dolores of southern Colorado, vertebrate fossils occur in several members all of which are described as conglomeratic.[1] The species from this area have not been identified as the same as those from Wyoming, and they seem to be quite distinct. Perhaps all of the genera are distinct, though this is uncertain. Professor M. G. Mehl says (personal communication) that no genus of phytosaur of Wyoming has been positively identified with any genus from Colorado, New Mexico, or Arizona, though phytosaurs constitute the greater part of the vertebrate remains from all of the localities. Several genera of amphibians are present, but no genus common to Wyoming and Colorado is known. This may be due to the fragmentary remains, which have permitted positive generic identification in only a few cases. The remains that have been identified as dinosaur are too scanty in most cases to make it sure that they belong to dinosaurs. Invertebrate remains which occur in the same members as the vertebrates in Arizona, New Mexico, and Wyoming, as worked out by W. F. Bailey in the University of Missouri laboratories, are entirely distinct in the various localities.

The Shinarump and Chinle of Arizona and New Mexico have

[1] S. H. Knight, *loc. cit.*

[2] Whitman Cross and Ernest Howe, *Bull. Geol. Soc. Amer.*, Vol. XVI (1905), pp. 467–69.

yielded more vertebrate fossils than any other Triassic formations of the red beds. The two are classed together on account of the impossibility of determining from the records whether vertebrate fossils have been obtained in one or the other, though the Shinarump as limited by Gregory to the lower 100 feet of conglomerates and sandstone has yielded few fossils. Great numbers of vertebrate fossils have been collected from the petrified forest near Adamana. All of the petrified-forest rocks were formerly classed as Shinarump, but present classification would place them in the Chinle. The extent of distribution of Chinle fossils is not definitely known. The writer has collected them through 300 or 400 feet, but collecting has been too patchy and records of collections too incomplete to distinguish members. Most of the species described have been based on skulls, more or less incomplete, and nearly every skull represents a species different from all the rest. All of the assemblages are of phytosaurs and labyrinthodonts similar to the association in the Keuper of Europe, but some of the American material may be Middle Triassic.

The emphasis here is on the uselessness of the fossils that have been described in making close correlations between the various areas. The presence of land animals as fossils in the sediments depended on conditions which allowed them to reach a place, rather than on time. The Popo Agie member should not be correlated with Jelm on the basis of its phytosaurs and amphibians while not a single genus is known to be common to both formations.

Correlation from south to north seems to be, roughly, Shinarump and Chinle in Arizona, New Mexico, and Utah, equal Dolores in Colorado, equal Middle Chugwater in Wyoming, equal Thaynes and Ankereh in Idaho, northwestern Colorado, and northeast Utah, equal Dockum of eastern New Mexico and western Texas. This presents nothing new save the emphasis on the failure of the fossils definitely to indicate exact correlation, and the placing of middle Chugwater rather than the upper as equivalent to the Chinle.

Von Huene[1] has listed the Triassic fossils in definite horizons. The writer's collecting, which has covered most of the localities listed

[1] F. R. von Huene, "Notes on the Age of the Continental Triassic Beds in North America with Remarks on Some Fossil Vertebrates," *Proc. U.S. Nat. Mus.*, Vol. LXIX, pp. 1–10.

by von Huene and a great many others and Dr. Mehl's collecting during several summers from the Chinle in Arizona and New Mexico have failed to check with the list. Many of the collections listed by von Huene were made without any check as to the horizon. After a study of abundant material in the University of Missouri collections, Mehl concludes that there is as yet no evidence of the genus *Angistorhinus* outside of Wyoming. Further, he feels that the specimen from the Wingate, New Mexico, region, referred doubtfully to *Paleorhinus* by Toepelman,[1] should not be used for stratigraphic purposes. The remains are very meager and suggest at best a primitive phytosaur. The genus was named from the Popo Agie beds of Wyoming and has not been found elsewhere.

Both von Huene and Berry[2] were in error in their conception of the Popo Agie beds. As noted in another paragraph, these beds do not constitute the top of the Chugwater, as stated by von Huene, but are some 600 feet below the top. In his original description of the Popo Agie beds Williston said: "The beds whence the fossils were obtained, from forty to eighty feet in thickness, are about two hundred feet below the top of the red-beds and about six hundred feet above the base."[3] The error in thickness was due to the writer, who had charge of the University of Chicago collecting party in Wyoming during the summer of 1904. The thicknesses were estimated rather than measured, and it was not until 1911 that the measurements published by Branson[4] in 1915 were made. Berry[5] quotes Williston, but one would gather from a later paragraph that he considers that the red beds from the Popo Agie member to the top should be called Popo Agie and are equivalent to the Jelm.

Merely to complete the Triassic correlation, the writer has listed the Lower Triassic beds in the correlation table. He has nothing to add to published data concerning their correlation. The placing of

[1] W. C. Toepelman, "Phytosaur Remains from New Mexico," *Quart. Bull. Univ. Oklahoma, University Studies No. 5* (1916), pp. 40–44.

[2] E. W. Berry, *op. cit.*

[3] S. W. Williston, "Notice of Some New Reptiles from the Upper Trias of Wyoming," *Jour. Geol.*, Vol. XII, p. 688.

[4] E. B. Branson, "Origin of the Red Beds of Western Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XXVI, pp. 220–21.

[5] *Op. cit.*, p. 489.

the Dinwoody in the Triassic, according to recent usage, is without published data to warrant it. There seems to be no unconformity between Dinwoody and Phosphoria where the writer has examined the contact, and there is an unconformity between the Dinwoody and Chugwater in some places.

In a discussion of a paper by S. H. Knight the writer is on record as saying that the Popo Agie beds lie unconformably on the sandstones below.[1] This unconformity may be no greater than that caused by topset beds of a delta being deposited over the slightly irregular foreset beds.

ORIGIN

The main object of this paper is a review of the old question of the origin of the red beds of the Rocky Mountain region. The assumptions by some writers that the sediments are of continental origin are not in harmony with the conclusions of the writer and some others[2] who have investigated the formations extensively. In order to be specific, the discussion in the following pages hinges on the Chugwater formation, with only incidental references to the other red-bed formations.

TWO TYPES OF LITHOLOGY

The Chugwater has two sharply contrasted types of lithology, which the writer has compared in his paper on the "Origin of the Red Beds of Western Wyoming."[3] In one phase the beds are uniform in thickness over wide areas, uniform in texture over wide areas, extensively ripple marked; thin and persistent limestone beds are present; beds of gypsum are of wide extent; sun cracks and fossils of land animals are absent.

In the other type the beds are discontinuous; change sharply from one kind of sediments to another; the sediments are not well sorted and the textures vary widely; no ripple marks are present;

[1] "Age and Origin of the Red Beds of Wyoming," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), p. 168.

[2] John B. Reeside *Jour. Geol.*, Vol. XXXII, p. 489. Quoted by Berry. D. Dale Condit, "Relations of Late Paleozoic and Early Mesozoic Formations of Southwestern Montana and Adjacent Parts of Wyoming," *U.S. Geol. Survey, Prof. Paper 120* (1918), p. 120.

[3] *Bull. Geol. Soc. Amer.*, Vol. XXVI, pp. 219–21.

limestones when present are conglomeratic; no gypsum beds are present; fossils of land and fresh water animals and plants are rather widely distributed.

In general these types are contrasted sharply enough to cause geologists to classify the one as "subaqueous" and the other as "subaerial" without question. However, the type that shows so clearly its subaqueous origin lacks not only fossils of land animals, but fossils of any kind. The lack of marine fossils has led many geologists to throw all of the other evidences in the discard and call those beds non-marine, though the beds also lack non-marine fossils, and beds of the other type associated with them do have non-marine fossils.

We may use as examples of the two types of lithology the Popo Agie beds and the rest of the Chugwater on the east slope of the Wind River Mountains in Wyoming. All of the Chugwater except the Popo Agie member has the characteristics of the subaqueous deposits. The Popo Agie beds are sharply contrasted. They are made up of sandy shales, mudstones, conglomerates, sandstones, and thin lenses of limestone. The mudstone shows little or no bedding. The bedding was probably destroyed in part by the mud cracking and the cracks filling with sand and wash as described by Barrell,[1] but good bedding may never have existed, as discussed in a later paragraph. Fragments of bone are widely distributed in the Popo Agie beds, though complete bones are rare.

ORIGIN OF THE POPO AGIE BEDS

The Popo Agie member was formed as topset beds of deltas and near-shore subaqueous deposits. That the area was submerged part of the time is indicated by the presence of oölites scattered here and there through the beds. Tarr[2] described the oölites and reached the conclusion that they were formed under water. After the Popo Agie beds formed, the seas readvanced and covered the area to considerable depth and stopped the formation of oölites, irregular beds, heterogeneous sediments, and the inclosure of land forms of fossils.

If one takes the view that the Chugwater is subaerial in origin, the Popo Agie beds, with their striking differences from the rest of

[1] Joseph Barrell, *Bull. Geol. Soc. Amer.*, Vol. XXIII (1912), p. 426.

[2] W. A. Tarr, *ibid.*, Vol. XXIX, pp. 587–600.

the formation, must be explained. One must justify assigning to the same origin beds that show all of the characteristics associated with subaerial and shallow-water deposits, and other beds that show none of them. The question of the presence of fossil vertebrates and plants in these beds and not in the rest of the formation must be met.

ORIGIN OF THE LOWER CHUGWATER

The lower Chugwater below the Popo Agie member is 800 feet thick and extends at least 300 miles east and west and 300 north and south. The sediments are uniform in texture and the beds are uniform and extensive. The formation contains one limestone member of wide extent, several other limestone members, and gypsum members of wide extent. Twenhofel says:

> The wide extent of the gypsum and carbonate beds proves a nearly flat land subject to occasional flooding, prolonged evaporation, and the presence of an agent with the ability to produce wide and fairly uniform distribution. The conditions are best found on the flat, alluvial fans and deltas of regions which are somewhat semi-arid to arid. This environment would permit the development of lakes with lacustrine deposits, and at the same time the conditions would be favorable for the occasional development of eolian deposits.[1]

Twenhofel was summarizing literature and not giving results of personal investigations of the Rocky Mountain red beds.

Tomlinson[2] has given the most extensive general report on the red beds, but his report was based more largely on the literature than on personal observations, though he had spent two summers in the field in Wyoming and Idaho. Tomlinson says:

> The types of sediments probably most important in the Red Beds group are stream deposits, submarine fluviatile deposits, and playa deposits, all predominantly of red color and all deriving at least the greater part of their ferric oxide from ferruginous residual soils. Of these the first is by all odds the most important.

Tieje[3] reaches mixed conclusions in his discussion of the origin of red beds of the Front Range. The "Lykins formation is chiefly an

[1] William H. Twenhofel, *Treatise on Sedimentation*, p. 178.

[2] C. W. Tomlinson, "The Origin of the Red Beds," *Jour. Geol.*, Vol. XXIV (1916), pp. 153–79 and 238–53.

[3] A. J. Tieje, "The Red Beds of the Front Range of Colorado: a Study in Sedimentation," *Jour. Geol.*, Vol. XXXI, pp. 192–207.

upper-delta formation," that is, subaerial delta, according to him. In his discussion he assigns to wind the main work of sorting and rounding the grains.

Recent papers by Dorsey[1] and Raymond[2] deal with origin and retention of color. Dorsey draws sweeping conclusions concerning origin of red sediments, but his conclusions could not apply to the western red beds.

TOPSET BEDS OF DELTAS

Topset beds of deltas are never uniform in texture and thickness over wide areas. The beds are interrupted by old channel deposits, lake deposits, deposits of irregular currents, etc. The sorting of sediments is only rarely and locally of high perfection. Silts are mixed with sands and shales are sandy.

The sorting of the sediments in much of the Chugwater is remarkable. As an example, the composition of one bed of wide extent and uniform thickness is as follows:

In 75 per cent of the mass the grains range between .074 mm. and 147 mm.
In 9 per cent of the mass the grains range below .074, but very few grains are as small as .04 mm. and none as small as .01.
In 14 per cent of the mass the grains range between .147 mm. and .295 mm.
In .15 per cent of the mass the grains range between .295 and .589 mm. The percentage is too large, as some of the grains are made up of several grains of smaller size.
No grain above .5 mm. was found.[3]

If it be postulated that part of the Lower Chugwater was formed as topset beds of a great delta, it must be assumed also that foreset and bottomset beds were formed at the same time. A great interior sea must have existed for a long time to receive the sediments brought down by the rivers that formed the topset beds. The sea must have covered Wyoming, parts of Montana, South Dakota, Nebraska, and Colorado. As the beds thin eastward, the streams must have come in from the west. No extensive marine deposits to

[1] George Dorsey, "The Origin of the Red Beds," *ibid.*, Vol. XXXIV (1926), pp. 131–43.

[2] P. E. Raymond, "The Significance of Red Color in Sediments," *Amer. Jour. Sci.*, Vol. XIII, pp. 234–52.

[3] The data were taken from a series of detailed studies of red-bed members that are being made in the laboratories at the University of Missiouri.

correlate with such topset beds have been found. Furthermore, such great thickness of topset beds without interbedded marine strata would not form. Such a very widespread topset area would have been ideal for phytosaurs, amphibians, and plants, but none has been found below the Popo Agie member.

Students in the field readily differentiate between the Green River lacustrine deposits and Wasatch continental deposits of the Eocene. Some members of these deposits are of the same age and interfinger.[1] The Chugwater is in contact with the Wasatch near Dubois, Wyoming, and at no place, excepting in the Popo Agie member, does it display any of the continental characteristics of the Wasatch. In these outcrops one may observe the striking contrasts in the formations, find in one all of the criteria for marine deposits save marine fossils, and in the other all of the characteristics of land deposits including land fossils. The Popo Agie member is near the Wasatch and could be distinguished only by its fossils from some phases of the Wasatch. No geologist working in the field on the Wasatch and Chugwater would assign their origin to the same agent. The Chugwater does not change from continental to lacustrine along any member. There are no evidences of dried-up lakes or of eolian deposits at the same levels. Twenhofel seems to assign to rivers flowing over low areas the duty of producing "widespread and fairly uniform distribution." Low alluvial fans, topset beds of deltas, and flood-plain deposits all show irregularity of distribution, imperfect sorting, and abrupt changes in composition of beds along the strike. Over an area of about 100,000 square miles the Chugwater sands are nearly uniform in texture and the grains are well sorted. Streams do not sort materials with great perfection. That requires some depth of water that moves very slowly, or wind under certain conditions.

ORIGIN OF GYPSUM AND LIMESTONE BEDS

Widespread shallow lakes are suggested by Twenhofel as the places where gypsum and carbonate deposits might originate. As the Chugwater beds do not show shifting from continental to lacustrine, one lake would have to cover more than 100,000 square miles

[1] Wilmot H. Bradley, "Shore Phases of the Green River Formation in Northern Sweetwater County, Wyoming," *U.S. Geol. Survey, Prof. Paper 140* (1926), pp. 121–31.

or nearly all of the Chugwater area. The beds, with the exception of the Popo Agie member and possibly the Jelm, are either all continental or all lacustrine or all something else.

Geologists have rarely approached the problem of origin of gypsum from the quantitative point of view, and some of them have thus failed to nullify part of their own conclusions. Gypsum in the Chugwater is widespread and many of the beds are continuous over wide areas. The writer has shown[1] that the precipitation of gypsum from fresh waters would be exceedingly slow. In an area of the size postulated there can be no appeal to special conditions of streams with unusual amounts of calcium sulphate in solution. Drainage came in from all directions. There were no great deposits of gypsum in older beds from which to draw. When the gypsum was deposited, the surrounding region consisted of unconsolidated red sands. If the lake in which the gypsum was deposited was dry part of every year, or every few years, which would be necessary if the deposits are to be considered continental, all materials in solution in the lake waters would be precipitated every time the lake dried up. As a consequence, the deposit would be a heterogeneous mixture of all of the materials carried in solution by the incoming rivers, or about one-half dolomite and limestone, one-fourth of gypsum, one-eighth common salt, and one-tenth silica. But the area was arid, and as such regions are affected by strong winds, the deposits would be thoroughly mixed with windblown sand or dust. The Chugwater gypsum deposits are of high purity and could not have been deposited in any such manner.

Assuming an evaporation of 10 feet per year above precipitation and a calcium sulphate content of four hundred parts per million, an amount far beyond any reasonable probability where the water is supplied by many streams from various areas, it would take five hundred years for 1 foot of gypsum to form. In discussing the origin of the Chugwater gypsum the writer[2] assumed that the deposition was in more or less isolated lakes, but the Chugwater basins could not have been isolated, as there is no gradation from continental to lacustrine in the deposits.

The writer's assumptions[3] for the formation of 1 foot of gypsum

[1] *Op. cit.*, p. 225. [2] *Loc. cit.* [3] *Ibid.*, p. 226.

in nine thousand years were based on a normal amount of calcium sulphate in stream water and on normal rainfall and run-off. One could get a much faster rate by making other assumptions. Evaporation might be 10 feet per year, but the inflow drainage area sufficient to get that amount of water into a 100,000 square mile basin would have to be enormous. Where large areas are drained into few streams, compared to the rainfall, the run-off is small. Ten per cent would be high. Part of the region had to be arid to cause the lake to dry up during the summer and prevent the formations of subaqueous deposits. In a semi-arid region an annual rainfall of 20 inches might be assumed. A run-off of 10 per cent would amount to 2 inches per year. A drainage area of 6,000,000 square miles would be needed to furnish the water for the 100,000 square mile lake. Cut the evaporation to 5 feet per year and the drainage area would be reduced to 3,000,000 square miles, but the time necessary for the precipitation of 1 foot of gypsum would be doubled.

It may be assumed with a high degree of positiveness that the entire area was not arid, that the rainfall and run-off were much higher over part of the drainage basin. In that case the supply of water would be more constant and the lake would not dry up every season or intermittently. A condition like that of Great Salt Lake would result, which would not furnish any phase of Chugwater lithology. As shown by the writer,[1] the formation of widespread beds of relatively pure gypsum is impossible excepting under conditions of fairly deep water.

Twenhofel says that the limestones could be formed in the intermittent lakes. In the Chugwater there is a limestone about 750 feet from the base. It is widespread and varies from 1 to 8 feet in thickness. If this were deposited from fresh water it would mean the evaporation of at least 10,000 feet of water to get 1 foot of limestone and 80,000 feet to get 8 feet. The most reasonable composition to take for this computation is that of the waters of the western tributaries of the Mississippi, as many of them flow through arid and semi-arid regions.[2] The average amount of calcium carbonate and magnesium

[1] *Ibid.*, p. 240.

[2] Frank Wigglesworth Clarke, "The Composition of the River and Lake Waters of the United States," *U.S. Geol. Survey, Prof. Paper 135*, p. 123.

carbonate in these waters is about 1:10,000 by volume, using all of the calcium and magnesium in calcium and carbonate magnesium carbonate.

One can scarcely imagine these arid basins holding back their other deposits while 10,000 feet of water evaporated at a rate that could not have been greater than 10 feet per year and deposited a foot of limestone, and the wind blowing no sand to mix with the lime for a thousand years. According to Twenhofel's hypothesis, this basin was not continuously covered with water, but was evaporated to dryness periodically. Of course it would be impossible to get a pure limestone or mixed limestone and dolomite under such conditions. Silica, gypsum, salt, and sand would be mixed with the lime.

WHY FOSSILS ARE ABSENT

The absence of marine fossils in the red beds has been used frequently as an indication of non-marine origin. Since land forms are present in one member of the Chugwater, it is much more difficult to explain their absence in the other parts than it is to explain the absence of marine fossils, particularly as the other ways of origin would be favorable for the preservation of land fossils. The writer has suggested that the reason for the absence of fossils was that the high salinity would have killed off most of the animals and plants. In the lower beds, as the Moenkopie in Utah and the Woodside and Thaynes in Idaho, fossils are present. The Moenkopie sparsely fossiliferous strata grade upward into the non-fossiliferous. The fossiliferous Thaynes grades upward into the non-fossiliferous Ankereh or Timothy. The absence of life in the seas also accounts for the persistence of the red color. Abundant life would act as a reducing agent and change the red colors.

RIPPLE MARKS AND THIN BEDS

During the last year the writer has been applying two new tests for distinguishing continental deposits from marine and lacustrine. He thought it logical to assume that extensive thin-bedded deposits could not form by means of subaerial agents, but only in rather quiet waters. He applied this test to the Wasatch, Wind River, Morrison, and other formations recognized as continental by generally

used criteria. At no place did he find extensive thin-bedded deposits, paper-thin shales or shales of ordinary bedding, or thin beds of well-sorted sand. The shales were all sandy and showed bedding by color variations rather than by true beds.

It seems impossible that extensive ripple marks could form and be preserved in flowing waters of streams. They do form in limited areas, and they form in the very shallow, almost stagnant waters of some parts of flood plains during floods, but they have very little chance to be preserved, and one would expect to find them only rarely in such deposits. In one summer's investigation on Morrison, Wasatch, and Wind River formations, no ripple marks were observed. The presence of ripple marks over large areas is sure evidence of subaqueous origin, and ripple marks associated with thin beds that do not grade abruptly into thick beds constitute positive evidence of deposition in extensive bodies of water, either lakes or oceans.

Both ripple marks and thin beds are extensively developed in the red beds.

ORIGIN OF UPPER CHUGWATER

Some geologists are willing to concede that the Chugwater below the Popo Agie beds is marine, but consider the overlying beds non-marine. Such conclusions can come only from those without extensive field experience on the formation. The Chugwater above the Popo Agie beds is much like that below save that it contains more sand. The writer suggested[1] that one highly cross-bedded member some 200 feet above the Popo Agie beds might be windblown. His supposition was based on the idea, prevalent at the time that the paper was written, that very striking cross-bedding was the work of wind. In the same area with the Chugwater the Tensleep sandstone shows cross-bedding just as striking, and marine fossils associated with the cross-bedding.

We may dismiss the flood plain, alluvial fan, topset beds on the same grounds as for the lower beds. The land animals that would have found such a region exactly suited to their living are absent. The deposits of the sea or inland body of water into which the rivers emptied as they formed deltas are absent. Well-sorted sediments in

[1] *Op. cit.*, p. 221.

even and widespread beds are present. The wind cannot make uniform beds of wide distribution and cannot produce ripple marks on large flat surfaces. Uniform beds and ripple marks on large flat surfaces are characteristic of the Upper Chugwater. It may not be possible to prove that one or two of the highly cross-bedded members are not wind deposits, but an appeal to such an origin is unnecessary.

OTHER RED-BED FORMATIONS

The preceding discussion has hinged on the Chugwater merely because that formation furnishes a well-known unit. The Moenkopie presents the same characteristics as the Chugwater save that no near-shore-landward phase has been noted excepting as mentioned in a later paragraph. But the near-shore-landward phase is present in parts of the Dolores of southwestern Colorado and in the Shinarump and Chinle of Arizona, Utah, and New Mexico. The La Plata, Navajo, and Wingate have none of the qualities of subaerial deposits. They are in the main thick bedded, and some of the beds are remarkably thick. The thick beds are usually cross-bedded, in part foreset beds of deltas. The beds do not change abruptly in composition. One may trace them for many miles without being able to detect any change in texture or thickness of beds. Ripple marks are common. No land fossils have been found save a so-called dinosaur footprint in the Todilto, which lies between the Wingate and Navajo and seems to be of the same origin.

The Chinle formation is in part subaerial, probably topset beds of a great delta. Its materials are not well sorted; its shale beds are intangible and are made up mainly of poorly sorted materials; it does not have ripple marks; it bears land vertebrates in many members and freshwater invertebrates in the same members; its beds change abruptly in thickness and composition; it bears many pieces of fossil wood.

The writer has been unable positively to verify his belief that part of the Chinle is contemporaneous with the Moenkopie and represents the topset beds of a great delta while the Moenkopie was forming under the sea. The Chinle seems to be in part contemporaneous with the Wingate. The sea was advancing eastward in Wingate time, and the landward part of the delta was more and more restrict-

ed in extent, the Dockum beds of Texas probably representing its last phase. The Moenkopie probably interfingers into the Chinle much as the Green River fingers into the Wasatch, and the Wingate and Chinle relationship is much the same. A great deal of the upper part of the Chinle in western New Mexico is marine in origin. Limestone beds appear; land fossils and fossil wood are no longer present; the beds become uniform in texture and are ripple marked.

The writer has examined the Nugget only at the east end of the Uinta Mountains, but the descriptions of the beds seem to place them in the same class as the Chugwater. No subaerial members have been described, though the formation is usually referred to as non-marine. Like most of the Chugwater, it does not bear marine fossils.

THE CHINLE DELTA

The great Chinle delta fits into a paleogeography that seems workable. The uplift of the Appalachians diverted much drainage to the northward to the general region of the Ohio River, but the mountains of Arkansas, Missouri, and Oklahoma forced the river to flow across northern Missouri, southern Kansas, northwestern Oklahoma, northwestern Texas, and into New Mexico. The river drained an area comparable in size to the drainage basin of the Mississippi. In crossing Oklahoma and Texas it acquired great quantities of red sands and muds from the Permian, much as the Amazon gets the red color for its sediments from the lower reaches. If the sediment carried by the river was comparable in amount to that carried by the Mississippi, it may have furnished the sand and clay for half of the 300,000 square miles of red sandstone and shales of the Triassic red beds at a rate of 1 foot every five hundred years.

The writer does not intend to imply that this was the only source of red sediments or even the main source. The entire region surrounding the inland sea in which the red beds formed must have furnished red sediments, for the reds are present through the entire extent.

However, not all parts of the formations are red. The Navajo is white or gray over large areas. The La Plata lacks red color in many places. Even the Chugwater contains non-red beds. The red color is independent of the question of marine or non-marine origin, and has not been investigated during the writer's studies.

EOLIAN ORIGIN

Perhaps the question of the possible eolian origin of considerable parts of Wingate, Navajo, La Plata, and Chugwater should not be dismissed as summarily as by Twenhofel[1] in the "Treatise on Sedimentation." The writer is in agreement with Twenhofel in considering such origin as clearly impossible. Winds do not create widespread beds of even thickness; wind deposits are not ripple marked on extensive surfaces; extensive wind deposits vary greatly in texture from coarse, well-rounded almost pure quartz sand, on the one hand, to heterogeneous loesslike deposits, to fine silt deposits. It has been rather generally assumed that wind deposits should have well-

Measurements in Millimeters	Chugwater	Windblown
Below .074	9 per cent	11.9 per cent; no grains; well rounded.
.074–.147	75 per cent 1/50 well rounded	48.6 per cent; no grains; well rounded
.147–.295	14 per cent 1/10 well rounded	39.2 per cent; no grains; well rounded
.295–.589	1.5 per cent ½ well rounded	.3 per cent; a few grains; well rounded

No grains above .589 mm. in either sand
40 gm. of Chugwater tested; 117 gm. of windblown tested

rounded grains and be uniform in texture and composition. This is true of the fairly coarse windblown sands, but where the modal grains are less than ¼ mm. in size the materials are highly heterogeneous and the grains are mainly angular. In areas of dunes composed of fine sands derived from the red beds, the materials are more heterogeneous in texture than those of the red beds. The composition of sand from one bed of the Chugwater is given on page 621 of this paper. The composition of a windblown sand of wide distribution in Estancia Valley, New Mexico, may be compared with the Chugwater sand. It accumulated to a depth of several feet in sheltered places and forms the main soil over hundreds of square miles. The sand was selected because the modal grains are of the same size as the modal grains of the Chugwater sand.

The most striking difference between these sands is in the part below .074 mm. In the windblown an appreciable amount ranges to

[1] *Op. cit.*, p. 178.

1/100 of a millimeter and below, while in the Chugwater no grains run below 1/25 of a millimeter. Windblown material of this grade is far more heterogeneous than materials deposited in quiet waters.[1]

Fine dune sand, loess, and adobe are windblown deposits much more heterogeneous than deposits in bodies of water. Small parts of the Chinle are loesslike. In an area of deposition as large as that covered by the Wingate, Navajo, or any of the red-bed sands, the fine dune sand, loess, and adobe should be much larger in amount than the coarse dune sand, but the sands of all of these formations are remarkably well sorted.

CONCLUSIONS

The Triassic-Jurassic red beds of the Rocky Mountain region should be correlated as shown in Fig. 3.

Vertebrate fossils are of little value in correlating various red-bed members.

Most of the red beds are marine in origin. They have the following diagnostic characters: (1) even bedding, (2) persistent beds, (3) sediments well sorted, (4) beds extensively ripple marked, (5) a great deal of thin bedding, (6) extensive gypsum beds in many places, (7) many extensive limestone beds, (8) no fossils of land animals, (9) no grading from subaqueous to subaerial sediments.

The non-marine red beds have the following diagnostic characters: (1) bedding uneven, (2) beds not persistent, (3) sediments poorly sorted, (4) no ripple marking, (5) no thin beds, (6) no gypsum beds, (7) limestone beds very thin and usually brecciated, (8) fossils of land animals present.

A large river flowed westward north of the Appalachians and emptied into the Triassic sea in New Mexico.

No appreciable amount of the red beds was eolian in origin.

[1] From a series of tests on windblown and waterlaid materials being made in the laboratories of the University of Missouri.

CORROSION AND CORRASION ON BARTON CREEK, AUSTIN, TEXAS

PHILIP B. KING
Austin, Texas

ABSTRACT

At a locality on Barton Creek, near Austin, Texas, the stream flows across horizontal layers of alternating hard and soft limestone. The bed-rock channel is incised by a number of long parallel grooves whose smoothed surfaces and U-shaped profiles are interpreted as a result of corrasion. On higher benches similar grooves occur at levels not now reached by the water of the stream, which are now being corroded by standing water, resulting in pitting of their smooth surfaces and in the formation of flat-floored, steep-walled basins known as tinajitas or etched potholes. The origin of the tinajitas is discussed. It is concluded that the features described are a result of the downward cutting of a youthful stream in a semi-arid climate, with a change from corrasive work to corrosive work on the valley-side benches as the stream cuts below them.

During recent months the writer has had opportunity to study some of the effects of erosion upon the limestones along the channel of Barton Creek, southwest of Austin, Texas. At one place in particular the forms displayed, and the relationships between the different forms, seemed to be of significance in suggesting the sequence of events which has taken place along the channels of many streams in the semi-arid limestone areas of Texas.

Barton Creek is an intermittent stream. At some seasons of the year it is entirely dry; during the greater portion its waters flow only across the bed-rock sills, sinking beneath the gravels in the reaches; while during occasional floods it is filled from bank to bank with rushing water. The stream is in youth of the present cycle, and at a locality about a mile upstream from Barton Springs it flows across horizontal ledges of Edwards limestone. The formation consists at this point of an alternation of hard massive layers of limestone, each from 2 to 3 feet in thickness, with thinner layers of more marly limestone. This causes the stream to descend in a series of steps. Below each step the channel is filled with great slabs of limestone, tilted this way and that, broken from the ledge above, and upstream from each step the stream is flowing on bed rock. On the sides of the chan-

nel higher limestone ledges rise in a series of benches, each from 10 to 30 feet in width (Fig. 1).

Immediately above one of the steps referred to, the bed rock channel of the stream is incised by a series of long grooves for a distance of perhaps fifty yards (Fig. 2). These increase gradually in width and depth from their upstream source, where these dimensions are scarcely more than a foot, to the margin of the step, where they

FIG. 1.—View looking upstream toward limestone benches during a time of moderately high water. Note bench in background well above present stream, and bench in foreground across which water is flowing in grooves. The level surface of this latter bench is extensively grooved in the middle distance.

reach a width of three feet and a depth of four feet. The grooves are nearly straight and parallel, following the general course of the stream, in places joining, in others bifurcating. Their bottoms are characterized by long gentle downstream descents, followed by abrupt rises. In the pockets thus formed potholes are often found. The surface of the limestone in the channel is smoothed and rounded by corrasion. Pits and jagged surfaces characteristic of corroded exposures of limestone were not seen.

At the margin of the step the grooves are cut so deeply that the soft layer beneath the limestone ledge has been penetrated. This has

aided in the break-up of the margin of the ledge. At this point water runs for the most part only in the bottoms of the deep grooves, leaving the upper surfaces of the ledge exposed for the greater part of the time. These upper surfaces show minute pitting and other evidences of incipient corrosion.

Above the bed-rock channel described, two broad benches are formed on higher limestone ledges which stand from 4 to 6 feet above

FIG. 2.—View of grooved channel upstream from margin of bench during low water. This area was submerged at the time Figure 1 was taken.

the limestone surface of the channel. These benches also show evidences of grooving and smoothing by corrasion, but it is clear that this process is no longer at work. Not infrequently the ledge is sharply broken off and the grooves terminate abruptly at the break, showing that the rock had been partly carried away after the grooves had formed.

Moreover, these waterworn surfaces exhibit clear evidences of subsequent corrosion. Some smoothed or undulatory surfaces of bare rock are pitted by numerous small ragged holes, characteristic of etched limestone surfaces (Figs. 3 and 4). In many cases also, tinajitas (etched potholes)[1] occur (Fig. 5). Some of these basins are

[1] J. A. Udden, "Etched Potholes," *University of Texas Bull. 2509*, p. 5.

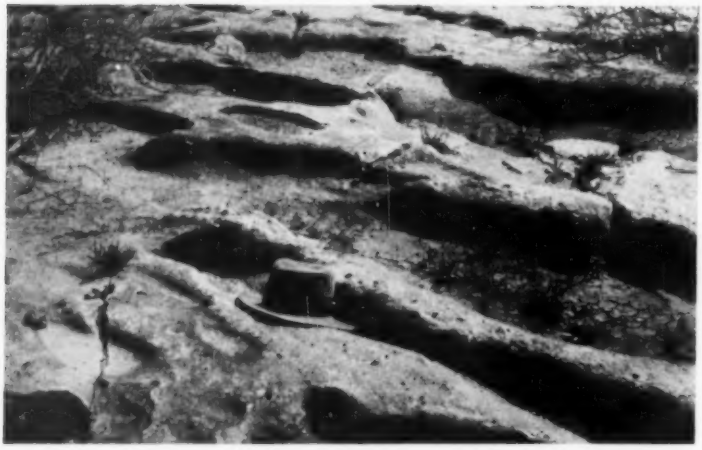

FIG. 3.—Surface of a higher bench. Parallel grooves are seen, in which tinajitas have formed. Note pitted surfaces, overhanging walls, and subcircular character of most of the basins.

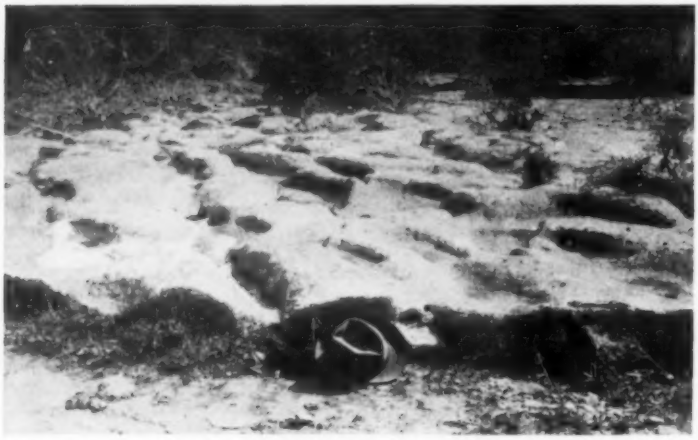

FIG. 4.—View in downstream direction of the bench shown in Figure 3. Note broken front surface of ledge and truncation of grooves along it, strongly suggesting that processes which formed the grooves are no longer at work.

found on level limestone surfaces, but most commonly at this locality they are found in the bottoms of the water-worn grooves, whose original deeper parts appear to have served as the starting-points for the etching process. There is a strong contrast between the smooth corraded grooves, with their U-shaped cross-sections and elongation parallel to the direction of flow of the stream, and these shallow, flat-bottomed, subcircular basins, with their steep and

FIG. 5.—Water-smoothed undulatory surface on first bench above channel, showing solution pits.

sometimes overhanging, fretted margins (Fig. 6). Many of the long, nearly straight grooves have been changed by corrosion into rows of connected, etched basins.

While these basins clearly originate from some sort of corrosion, there is some doubt as to the precise details of their formation. They are clearly the result of the work of standing water, as is seen by the contrast in the character of the higher limestone surfaces with the lower ones upon which running water is at work. The corrosive work appears to proceed sideward rather than downward, the flat bottom and shallow character of the basins, as well as the contrast between their smooth floors and their fretted margins, suggesting that the

solution takes place chiefly on the margin (Fig. 7). Udden,[1] who has studied these structures, gives the controlling factor as the work of

FIG. 6.—Sketches showing contrast between grooves formed by corrasion (*A*), and tinajitas formed by corrosion (*B*). The front surface of each block is about 3 feet in width.

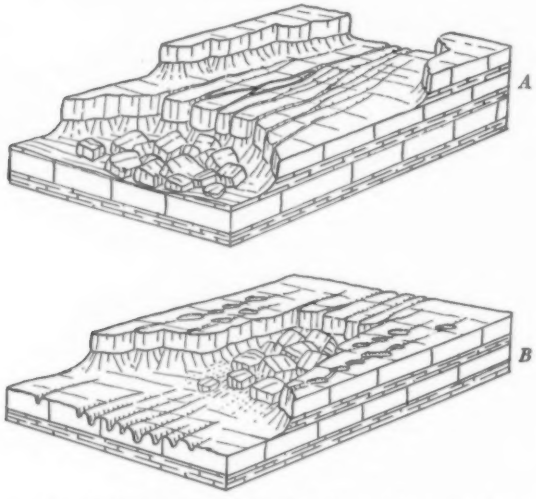

FIG. 7.—Stages in the processes outlined. (*A*) an early stage, showing grooved channel. (*B*) a later stage, showing retreat of ledge, and etching of grooves on valley-side benches across which the stream no longer flows. Front face of each block about 30 feet in width; vertical scale somewhat exaggerated.

gelatinous and other algae, such as chara and diatoms, that produce carbon dioxide. These are distributed during dry periods in hollows in the rocks, along with dust and soil, and are revived when these

[1] J. A. Udden, "Etched Potholes," *University of Texas Bull. 2509*, p. 7.

hollows are filled with water after rains. The carbon dioxide produced by their growth is believed by Udden to perform the etching process.

The manner in which the dissolved material is removed from the basins is not explained by him and is a matter which offers some difficulties, since the action takes place only in basins with no outlets. It may be that, upon evaporation of the pool, the dissolved material is precipitated on the level floor of the basin in the form of a loose calcareous earth, which is flushed out during the next succeeding rain or freshet, or is removed by the wind. Calcareous material, possibly of this origin, was noted in the bottoms of some of the basins at the locality discussed.

The stages by which these features are formed seem to be clear. Youthful Barton Creek, flowing on bed rock and degrading its channel, flows downward across a series of resistant benches. Where the channel crosses a resistant bench, it corrades downward by grooving, these grooves approximating average stream gradient by increasing in depth in a downstream direction. As the stream cuts deeper it cuts backward on each ledge, and those grooves formed by the corrading stream which are toward the side of the channel come to lie on valley-side benches well above the newer and lower drainage. The normal flow of the stream no longer reaches them or works upon them, and they are subjected to progressively longer periods during which they are dry. It is during these periods that the etching process takes place from water standing in depressions on their surfaces. This same process also acts to a limited degree upon the ledge in mid-stream at its downstream margin, as a result of the deep grooving here, but it seldom has opportunity to reach an advanced stage because this portion of the ledge is soon removed by the degrading stream. The net effect of these processes is toward corrasion in mid-channel, and corrosion in the high places in the channel and on the banks, where water is standing rather than moving.

When we consider the more general application of the processes outlined it becomes evident that the work of corrosion will increase in proportion to that of corrasion as the volume of a stream and the length of time which it flows decrease. These factors are governed chiefly by the size of the drainage area of the stream and by the

local rainfall. Thus, in the more arid districts we are to expect larger areas, in and adjacent to the stream, in which corrosion is predominant. In such districts etching will take place when there is merely sufficient rain to fill the tinajitas, whereas stream wear will occur only when the channel is flooded by heavy downpours.

These features are with little doubt merely an incident in the life of the stream, and disappear as maturity is reached. Nevertheless, their study and analysis may aid in understanding the characteristics of the channels and banks of streams of limestone areas in semi-arid regions.

NOTES REGARDING THE COALIFICATION PROCESS

D. J. FISHER
University of Chicago

ABSTRACT

With the aid of two triangular diagrams based on "as-received" ash-free proximate and ultimate coal analyses, a figure is drawn which shows in empirical fashion the *relative* losses of certain coal constituents during the coalification process. One of the triangular diagrams apparently offers a practical graphical scheme of coal classification.

The accompanying equilateral triangular diagrams illustrate in graphical manner the coalification process in terms of the coal constituents ("as received" ash-free basis) as determined by proximate (Fig. 1) and ultimate (Fig. 2) analyses made by the U.S. Bureau of Mines of some forty representative coals. Water was not deducted from the coal analyses used in preparing these diagrams, since no one questions the fact that the material analyzed as "moisture," present in relatively large amounts in peats and low-rank coals, is highly important because of its deleterious effect from the economic viewpoint. Both Ashley[1] and more recently Thom[2] have stressed the fact that it (at least in part) must be considered as a normal and characteristic coal component and cannot be regarded as more or less fortuitous, as is ash for instance.

> Peat freshly removed from an average bog usually contains 85 to 90 percent water. . . . . Most of this water exists in a form not like the water in a wet sponge but rather like that in jelly. This characteristic property of peat to retain water is the chief feature that has made the winning of peat fuel a speculative and an expensive process.[3]

[1] G. H. Ashley, "A Use Classification of Coal," *Trans. A. I. M. E.*, Vol. LXIII (1920), p. 783.

[2] W. T. Thom, Jr., "Moisture as a Component of the Volatile Matter of Coal," *Trans. A. I. M. E.*, Vol. LXXI (1925), pp. 282–88.

[3] W. W. Odell and O. P. Hood, "Possibilities for the Commercial Utilization of Peat," *U.S. Bur. of Mines Bull. 253* (1926), p. 8. See also H. C. Porter and O. C. Ralston, "Some Properties of the Water in Coal," *U.S. Bureau of Mines, Tech. Paper 113* (1916).

Figure 1 is somewhat analogous to Campbell's[1] well-known diagram showing the various coal ranks in terms of the ash-free proximate analysis constituents of typical examples, but lacks any impli-

FIG. 1.—Coal series ("as received" ash-free basis) in terms of proximate-analysis constituents. Heating value shown by numbers in thousands of British Thermal Units.

cation of the at present almost unknown volume changes that occur during the coalification process. Figure 1 very forcibly brings out the well-known fact, as expressed by Ashley[2] and others, that in terms of the proximate-analysis constituents, the coalification process represents dehydration in the earlier stages and devolatilization in the later stages.

[1] M. R. Campbell, "Coal Fields of the United States," *U.S. Geol. Survey Prof. Paper 100-A* (1922), p. 8.

[2] G. H. Ashley, *op. cit.*, p. 786.

The ultimate analysis component diagram presented in Figure 2 calls to mind the graphs of Grout[1] and of Ralston,[2] which however were based on the coal constituents as shown by ultimate analysis

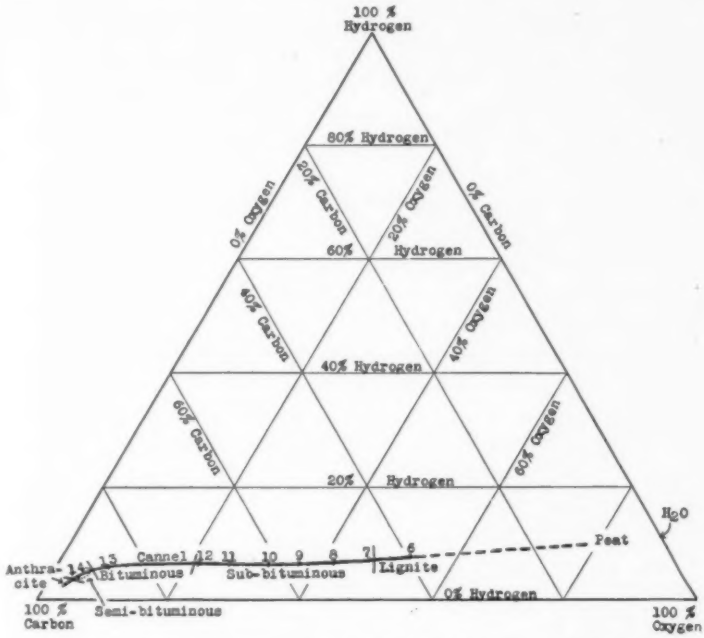

FIG. 2.—Coal series ("as received" ash-free basis) in terms of ultimate-analysis constituents. Heating value shown by numbers in thousands of British Thermal Units.

on a *moisture* and ash-free basis. The accompanying diagram extends the lower ranks and peat farther to the right, but other changes are minor. Semi-anthracites fall in a group too small to be clearly indicated on the scale used. The coalification process in terms of ultimate analysis constituents is seen to consist in the main of deoxidation, though dehydrogenization is also important in the earlier

[1] F. F. Grout, "The Composition of Coals," *Econ. Geol.*, Vol. II (1907), p. 227.

[2] O. C. Ralston, "Graphic Studies of Ultimate Analyses of Coals," *U.S. Bureau of Mines Tech. Paper 93* (1915). This reference gives a simple explanation of the general principles of the triangular diagram.

stages (up to medium-rank sub-bituminous) and later stages (high-rank bituminous and higher).

Studying one figure in light of the other brings out interesting relationships. The nearly right-angle bend in the "coalification curve" of Figure 1 is conspicuously absent from Figure 2, although both curves are based on different sorts of analyses of the same samples. The coal series is a continuous one, as is clearly shown by Figure 2, and lower and higher rank coals are not separated by any sharp division, as might be suggested by Figure 1. The explanation of the conspicuous bend in Figure 1 lies in part in the method of running the proximate analysis.[1] What is called "moisture" is that which comes off below an arbitrary temperature (105° C.) at which a one-gram sample of 60-mesh coal has been held for one hour. Later, on heating to 950° C. for seven minutes, additional water is driven off; but this is arbitrarily classed with the volatile matter.

Studied together, the two diagrams lead to the following conclusions: Considering only their *relative* implications, they indicate that the change from peat to lignite consists essentially of dehydration, though detailed data to prove this point are not at hand. From an early lignite stage to a late sub-bituminous or early bituminous stage, the coalification process consists mainly of dehydration, though devolatilization (Fig. 1) or loss of oxygen (Fig. 2), presumably as carbon-oxygen compounds rather than as the element, is of minor importance. The latter practically supplants dehydration through essentially all of the bituminous stage, however. Figure 3 is a rough attempt to show the changes diagrammatically.

That dehydration is of great importance in the early stages is much more apparent from Figure 1 than from Figure 2 because water by weight consists of only 11.2 per cent of hydrogen, and so, marked dehydration by weight does not mean marked dehydrogenization by weight. If the coalification process were simply one of dehydration, it would appear on Figure 2 as a straight line joining the H_2O-point on the right side of the diagram with the lower left-hand corner. This is the "carbo-hydrate line" or "zero available hydrogen line" of Ralston.[2] The right fifth of the coalification curve

[1] Stanton, Fieldner, and Selvig, "Methods of Analyzing Coal and Coke," *U.S. Bureau of Mines, Tech. Paper 8* (revised, 1926).

[2] O. C. Ralston, *op. cit.*, Plate I and p. 19.

of Figure 2 actually does appear to coincide essentially with such a straight line; but thereafter oxygen is lost at too fast a rate, as compared to hydrogen, for the latter to balance all of the former as water.

Figures 1 and 2 do not appear to be in perfect agreement as to the point where dehydration first becomes inactive during the coalification process. The former diagram indicates it is important up to an early bituminous stage, while the latter seems to show that it stops with medium-rank sub-bituminous. The former is probably nearer the truth in this matter, and so the tendency was to follow it in preparing Figure 3.

During and after the late bituminous stage, the devolatilization indicated in Figure 1 presumably means deoxidation *and* dehydro-

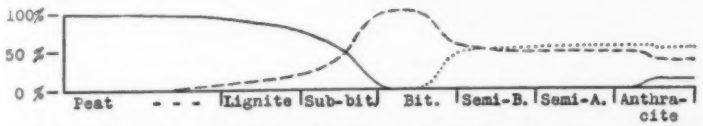

FIG. 3.—Diagram to show the *relative* losses of certain coal constituents during the coalification process. Solid line indicates "moisture"; dashed line, oxygen or carbon-oxygen compounds; dotted line, hydrogen or hydrocarbons. It is assumed that no carbon-hydrogen-oxygen compounds as such are lost during the process. The relative percentages by weight of the components lost are roughly shown by the ordinate-lengths. No implications are intended by the fact that the various ranks are indicated in terms of equal abscissa-lengths. See discussion in text.

genization as shown in Figures 2 and 3. It is assumed that no carbon-hydrogen-oxygen compounds, as such, are lost during these stages. It is possible that in the actual coalification process water, as such, is lost during and after the late bituminous stage. No renewal of so-called "dehydration" is shown by analysis, however, until well into the anthracite stage, according to Figure 1; and Figure 3 was drawn on this basis. Moreover, hydrogen is lost in much too large amounts as compared to the oxygen released during this part of the process for the two to balance as water. It is therefore considered that the oxygen and hydrogen lost in this period are possibly in small part in the elemental form, but are probably mainly driven off as carbon compounds, if the final minor dehydration indicated on the right side of Figure 3 be excepted.

It should be emphasized that the changes shown by these diagrams are only relative. Thus from peat to high-rank sub-bitumi-

nous, the change is said to be primarily one of dehydration. But it is known from observations in bogs and mines that hydro-carbon and oxy-carbon gases are lost during these stages. Figure 1 indicates, however, that, *relatively* considered, dehydration is of overwhelming importance, as the coalification curve goes almost directly away from the "100 per cent moisture" corner of the triangle. Moreover, it also indicates that during these stages the two "components" designated "fixed carbon" and "volatile matter" are lost in essentially equal weight-amounts, since the curve runs almost directly toward the middle of the base of the triangle. There is, however, a slight variation that indicates that in the first part of this change there is a slightly greater loss of fixed carbon than of volatile matter; while in the last part the reverse is true.

In discussing the coalification process, the writer realizes that the coal constituents he has used, namely, the products obtained during proximate or ultimate analysis, are greatly different from the largely unknown compounds present in the coal conglomerate itself. The chemical analytical process has in common with the coalification process the fact that both form a product consisting largely of carbon. In fact, in nature where igneous material has intruded coal beds, in some cases a product similar to that produced in the analytical laboratory is obtained, though the laboratory product is due solely to heat, whereas pressure and vapor action[1] as well as heat may be important in forming the natural product. But the intermediate steps through which the natural and artificial processes result in more or less similar end-products are probably almost totally different. Thus it must be borne in mind constantly that the accompanying diagrams, while they graphically illustrate the coalification process, do so in distinctly empirical and relative fashion. Loss of water, then oxygen, presumably in carbon-oxygen compounds, and lastly hydrogen, probably partly as water but mainly as hydrocarbons (with more or less overlapping), constitute the coalification process from this point of view. This gives some idea of the stability during the coalification process of the various compounds present in coal in terms of their constituents. For in-

[1] J. B. Eby, "Contact Metamorphism of Some Colorado Coals by Intrusives," *Trans. A. I. M. E.*, Vol. LXXI (1925), pp. 246–52.

stance, a minor portion of the "moisture" is apparently combined within the coal-conglomerate far more firmly than is the main part.

The points representing the analyses used fall on a nearly linear curve in Figure 2 but occupy a narrow to fairly wide zone in Figure 1. The analyses used were selected at random, with the limitation that they were all made fairly recently on carefully collected mine samples[1] of fresh coal. Since relatively few analyses were used, it is not safe to generalize too much; and it is realized that the curves given are only approximately correct. In part the nearly linear curve of Figure 2 is explained on the basis of care in sampling and the small size of the graph. The cannels carry about 1 per cent more hydrogen and so fall slightly above the curve. Variations in carbon and oxygen, on the other hand, would simply move the point representing a given analysis back and forth nearly along the line. Such variations as these last are indicated in the rather wide vertical zone of the Figure 1 curve, while the horizontal zone of this last curve is narrow, since the coals here represented have lost nearly all the material determined as "moisture" that they (as coals) ever do lose.

Either Figure 1 or Figure 2 could serve as a basis for a graphical coal classification, but the latter would be of little value since the higher ranks are not well differentiated on it. It would seem that Figure 1 would serve as a basis for a practical graphical scheme of classification despite frequent statements to the effect that water in coal is too variable to be of value in this connection. The diagram emphasizes the fact that if the proximate coal analysis by itself is of value in the classification of coal, moisture content must be the main factor determining coal rank below the bituminous stage. Obviously proof of this opinion would require the plotting of numerous analyses. This cannot now be justified, since, as pointed out so well by Thom[2] new standards of sampling, shipping, and analyzing

[1] The air-drying losses of the samples, the analyses of which were used in preparing the accompanying diagrams, are shown by the following figures. The average values, with variations, are given. Lignite, 32.3 ± 5; sub-bituminous, 14.7 ± 10; bituminous, 2.1 ± 1; cannel, 0.5 ± 0.1; semi-bituminous, 2.4 ± 0.5; semi-anthracite, 1.5 ± 0.6; anthracite, 1.5 ± 0.9.

[2] W. T. Thom, Jr., *op. cit.*, p. 285. If the accompanying curves are really representative of carefully sampled (in the mine) and analyzed coals, it would appear that

coal are necessary before there can be offered a reliable chemical basis of coal classification which makes use of the moisture content. Moreover, the main purpose in submitting this note is to offer an extremely simple graphical method of indicating the empirical and relative chemical changes which take place during the coalification process, and this object would be partly defeated if the first two diagrams showed a mass of dots instead of the two relatively simple and somewhat generalized curves.

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any new analytical methods developed would involve not only standardizing the humidity conditions under which the coal is dried, but also probably both raising the water-content of the air-drying atmosphere above that now used in average practice and lowering its temperature (30 to 35° C. at present). Such changes would be especially necessary for coals below bituminous rank (see the last footnote). The lowering of temperature would also result in less oxidation, but by substituting a drying atmosphere of some inert gas (possibly nitrogen) much better results in this respect could presumably be obtained.

THE RELATIVE EFFECTIVENESS OF BACTERIA AS AGENTS OF CHEMICAL DENUDATION

GEORGE A. THIEL
University of Minnesota

ABSTRACT

Data are presented that represent the results of a series of experiments conducted in an attempt to measure in quantitative terms the rôle of bacteria as agents of chemical weathering. Common igneous and sedimentary rocks were subjected to leaching under sterile conditions and under natural conditions, and the increase in salinity of the leaching solutions noted. By comparing the results obtained from all of the samples it was found that the total of the analyzed constituents was 53 per cent greater for the solutions with bacteria than for those leached under sterile conditions.

The early researches of Müntz, Widgradski, and others demonstrated that bacteria may play an important rôle in rock disintegration and decomposition,[1] but the magnitude of their influence has never been expressed in any quantitative terms. Furthermore, owing to the uncertain variations of conditions that exist at and near the surface in the zone of rock decay, an accurate determination of the influence of bacterial activity must long remain an unmeasured factor. However, more accurate approximations can be made from experimental data obtained under controlled laboratory conditions than from field estimations where organic material is promiscuously distributed. The effects of biochemical reactions at any one point may be small, but in the aggregate they become appreciable.

The object of this paper is to present the results of a series of experiments dealing with the relative effectiveness of bacteria in affecting the solution of mineral aggregates that form the common igneous and sedimentary rocks.

MATERIALS AND METHODS

The following rocks, representing a series from the acidic to the basic igneous rocks, and a typical argillaceous sediment and a ferruginous chert were used in the experiment: (1) coarse-grained horn-

[1] A. Müntz, *Annales chim. phys.* (6th ser.), Vol. XI, 1887.

blende-biotite granite with large pink orthoclase grains and finely granular quartz—orthoclase predominant; (2) coarsely granitoid hornblende syenite; (3) hornblende-biotite monzonite with orthoclase and plagioclase present in approximately equal amounts; (4) quartz diorite with hornblende predominant; (5) diabasic gabbro—medium grained; (6) Decorah shale—a somewhat calcareous stratum in green shale; (7) ferruginous chert from the Biwabik iron formation, Mesabi range.

TABLE I

PARTIAL ANALYSES OF SOLUTIONS EMPLOYED, BEFORE AND AFTER LEACHING; RESULTS REPORTED IN PARTS PER MILLION (G. WARD, ANALYST)

Sample		SiO_2	Ca	Mg	Fe_2O_3	Al_2O_3	Na	K
Stock solution of spring water		6.40	26.60	15.60	0.05	0.52	11.6	3.40
No. 1. Granite	With bacteria	13.80	94.40	46.40	.23	.77	61.6	30.40
	Sterile	14.00	56.60	39.10	.17	.43	40.0	29.50
No. 2. Syenite	With bacteria	17.00	89.80	32.30	.20	.60	77.80	39.10
	Sterile	10.80	56.70	19.10	.11	.29	26.10	31.90
No. 3. Monzonite	With bacteria	20.20	118.50	35.20	.68	.32	82.50	36.80
	Sterile	10.60	56.60	27.50	.12	.48	63.20	21.10
No. 4. Diorite	With bacteria	30.60	93.60	43.50	.26	.34	94.90	54.80
	Sterile	14.00	56.60	23.00	.12	.68	42.30	20.00
No. 5. Basalt	With bacteria	7.40	100.40	33.60	.12	.68	44.20	22.10
	Sterile	9.00	73.00	22.10	.08	.51	36.40	14.10
No. 6. Shale	With bacteria	14.40	125.30	70.70	.12	.88	45.20	12.10
	Sterile	18.80	77.90	44.30	.08	.12	25.00	15.80
No. 7. Ferrug. chert	With bacteria	11.60	90.20	63.10	.18	.83	35.20	23.30
	Sterile	9.60	66.20	55.90	0.12	0.48	35.90	14.60

The rocks were crushed to pass an 80-mesh screen. Equal amounts (300 cc.) were placed in 500-cc. flasks each fitted with a drain and stop-cock at the lower margin to allow the leaching solutions to percolate through the crushed rock and drain into a container. A stock supply of leaching solution was prepared to insure uniformity of composition for the whole series. The solution consisted of natural spring water, to which was added 100 cc. per liter of a filtered extract washed from the black mud in the pool of the spring. The extract was added to insure the presence of organic constituents for bacterial growth. The salinity of the stock solution is given in Table I.

Two sets of leaching experiments were arranged, one duplicating natural conditions and the other with all materials sterilized.

SERIES A. (UNDER NATURAL CONDITIONS)

Several grams of fresh, black, loamy soil were added to the crushed rock and enough stock solution introduced to thoroughly saturate the contents of each flask. They were then allowed to stand unstoppered for five days to allow the soil bacteria to multiply and permeate the rock samples. No prepared cultures of any type of bacteria were added. The spring water was then introduced a drop at a time by means of a siphon fitted with a pinch-cock control. The solution penetrated the crushed-rock samples and the leachings dripped through a filter into a container.

SERIES B. (UNDER STERILE CONDITIONS)

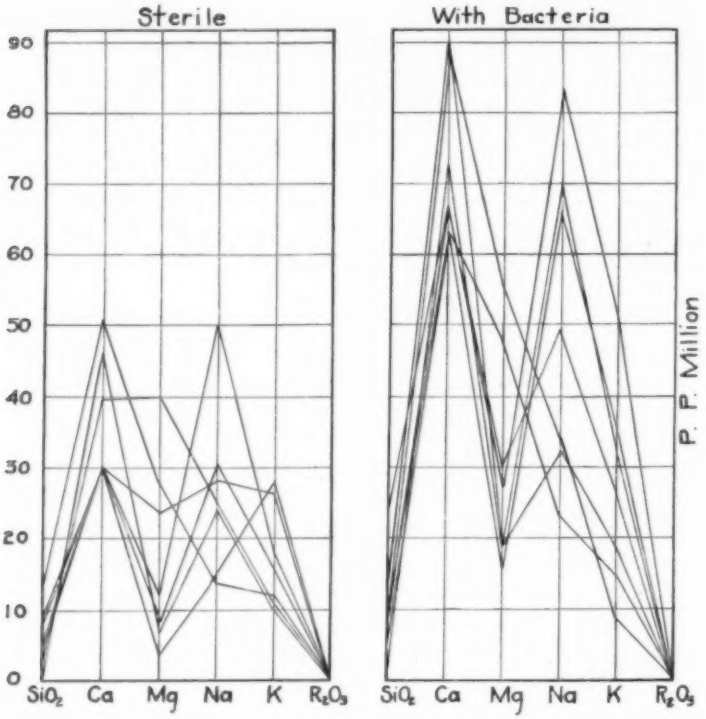
The apparatus and material of Series A was duplicated but without the small amount of soil and with all material sterilized. Since the solubility of mineral constituents may be modified by heating, the rock samples were not subjected to heat treatment for sterilization. Very few organisms other than air-contaminating forms could thrive in clean, dry rock powder. All glassware was sterilized by means of dry heat and the solutions placed in an autoclave at 20-pound pressure for twenty-five minutes. In order to maintain uniform conditions, this series was also allowed to stand five days with the samples saturated with the leaching solutions, but the flasks were loosely plugged with dry cotton stoppers to prevent contamination.

The rate of leaching was kept as uniform as possible for both series, and after a liter of solution had percolated through each sample, the leachings were analyzed and the salinity recorded in radicles or ions in accordance with the methods used in water analyses.[1]

Table I shows the analysis of the natural spring water used in the experiments, together with the salinity of the water after it had percolated through the crushed rock under sterile conditions and under natural conditions with bacteria. Figures 1 and 2 show the same results plotted graphically in composite curves. The percentage in-

[1] F. W. Clarke, "The Composition of River and Lake Waters, etc.," *U.S. Geol. Survey Prof. Paper 135.*

crease of constituents taken from the rocks due to biochemical reactions is given in Table II. By a compilation of the results obtained for each sample, it is found that the total of the analyzed constitu-



Figs. 1 and 2.—Composite curves showing the relative effectiveness of bacteria as agents of chemical denudation. A graphic representation of the analyses in Table I.

ents is 53 per cent greater for the solutions with bacteria than for those leached under sterile conditions. The increase in lime and soda is the most outstanding when plotted in terms of parts per million as shown in Figure 2; however, when calculated in terms of percentage increase over the sterile solution, even the iron and alumina show a marked increase.

The comparatively small increase in salinity obtained from sam-

ples Nos. 6 and 7 (see Table II) may be readily explained on the basis of the character of the rocks involved. Number 6 is a slightly dolomitic shale, and inasmuch as shale is composed mainly of the clastic remains of chemically disintegrated rocks, most of its soluble constituents were removed during the preceding cycles of erosion. Sample 7, because of its siliceous character, contributed a smaller percentage than either of the other rocks.

TABLE II

PERCENTAGE INCREASE IN SALINITY DUE TO BIOCHEMICAL REACTIONS

Sample Nos.	SiO_3 Per Cent	Ca Per Cent	Mg Per Cent	Fe_2O_3 Per Cent	Al_2O_3 Per Cent	Na Per Cent	K Per Cent
1	−11	130	31	35	48	76	10
2	140	110	370	81	15	350	25
3	230	203	63	460	−64	37	78
4	215	129	270	110	80	160	220
5	−40	56	170	50	31	31	74
6	−53	73	92	50	69	150	−51
7	62	35	17	50	59	00	77

POSSIBLE NATURE OF REACTIONS INVOLVED

Since carbonates form about 50 per cent of the solid compounds held in solution by the average river and lake waters,[1] it is considered that carbonated waters are the most active natural-occurring solvents of rock minerals. It has been commonly assumed that such waters come primarily from rain water charged with carbonic acid. However, the results tabulated above indicate that bacterial activity may be instrumental in increasing the amount of available carbon dioxide and thereby increase the solvent power of ground waters. Some groups of organisms produce many acids, and under favorable conditions certain forms can generate one and three-tenths times their own weight of carbon dioxide in twenty-four hours.[2] Twelve out of twenty varieties of bacteria isolated from ordinary loamy soil exerted a definite solvent action on the mineral constituents of the soil.[3] Some of these acted by means of carbon dioxide, others by means of organic acids. Most organic acids, however, are readily

[1] Clarke, *op. cit.*, p. 5.

[2] J. E. Greaves, *Bacteria, etc.* (New York: Van Nostrand Co., 1925), p. 18.

[3] *Ibid.*

oxidized to CO_2. Furthermore, the organisms also aid in bringing about the decomposition of organic tissue, and in this way enormous quantities of CO_2 are generated.

Sulphates rank next to carbonates in the list of solid contents of meteoric ground waters, and where they are abundant the composition of the ground water is subject to modification through the activity of the micro-organisms that decompose sulphates with the production of sulphides.[1] Undoubtedly the oxidation and partial solution of the resulting iron sulphide is the chief factor in the formation of the sulphate waters. Through the biochemical reactions initiated by these organisms, more extensive leaching of rock constituents is possible, for some of the sulphates are retained in the mantle rock, where they pass through cycles of reactions from sulphates to sulphides and back to sulphates. In the absence of the reducing environment developed by the micro-organisms, the sulphate solutions would be carried away by circulating ground water before the precipitation of sulphide could be accomplished.

Temperature changes resulting in expansion or contraction of the rock minerals aid the biochemical reactions by forming microscopic fractures along which the organisms gain access into the rocks. The bacteria, being of microscopic size, enter the small crevices and their products of metabolism aid in dissolving the rock. This method of operation in sulphate waters was demonstrated by suspending thin sections of rocks in culture solutions. In ten days the fractures in the rock sections were filled with freshly precipitated black iron sulphide which, when exposed to the action of the atmosphere, was oxidized to a yellow limonitic stain such as is commonly seen along fissures in sections of slightly weathered rocks.

[1] E. S. Bastin, "The Problem of the Natural Reduction of Sulphates," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. X, 1926; "A Hypothesis of Bacterial Influence in the Genesis of Certain Sulphide Ores," *Jour. Geol.*, Vol. XXXIV, 1926. George A. Thiel, "The Influence of Bacterial Action in the Deposition of the Kupferschiefer in Germany," *Econ. Geol.*, Vol. XXI, 1926; "Manganese Precipitated by Microorganisms," *ibid.*, Vol. X, 1925; "The Secondary Enrichment of Bauxite Ores through the Action of Micro-organisms," *ibid.* (In press.)

EFFECTS OF INCLUSIONS IN SMALL PORPHYRY DIKES AT CORNUCOPIA, OREGON

G. E. GOODSPEED
University of Washington

ABSTRACT

Certain porphyry dikes related to a batholithic intrusion in the Blue Mountain area of northeastern Oregon contain irregular segregations of magmatic residuals and veins which are believed to have been caused by the action of the dike magma upon schist inclusions. Many large-scale occurrences similar to this have been recorded, but it is believed that the small size of this magmatic system, dikes less than 2 feet in width, makes it a rather noteworthy occurrence.

Cornucopia is a small mining district of Baker County, in northeastern Oregon, and is situated at the southeastern edge of the rugged Wallowa Mountains. Lindgren's report on the Gold Belt of the Blue Mountains furnishes most of the source material that has yet been published with regard to the general geology of this region.[1]

The oldest rocks of the district which are supposed to be Triassic are sediments and intercalated volcanics, closely folded, now metamorphosed into schists, greenstone, serpentine, and some crystalline limestone. Contemporaneous with or immediately following the orogeny at the close of the Jurassic or at the beginning of the Cretaceous, came a batholithic intrusion of granodiorite. Elevation and erosion to maturity was followed in the Miocene by vast fissure eruptions of basaltic lavas, the dike feeders being especially abundant in this vicinity. Later elevation, followed by severe mountain glaciation, affords excellent exposures of the older rocks. The mineral deposits are genetically related to the batholithic intrusion. Some of the quartz veins have been much broken up by the later basalt dikes intruded along or cross-cutting them.

The many offshoots of the batholithic mass are represented by porphyries, granophyres, porphyritic aplites, aplites, quartz dikes, and quartz veins. The larger examples of the latter type represent

[1] Waldemar Lindgren, "The Gold Belt of the Blue Mountains of Oregon," U.S.G.S *22d Annual Report*, Vol. II, pp. 561–776.

the later phases of the magma. For the most part the dikes are rather uniform in texture and mineral composition, yet some which contain schist inclusions show a very peculiar veined structure. The study of thin sections and polished surfaces from these dikes has shown that certain changes and products of differentiation in small magmatic systems may bear somewhat of an analogy to the larger-scale changes of batholithic masses.

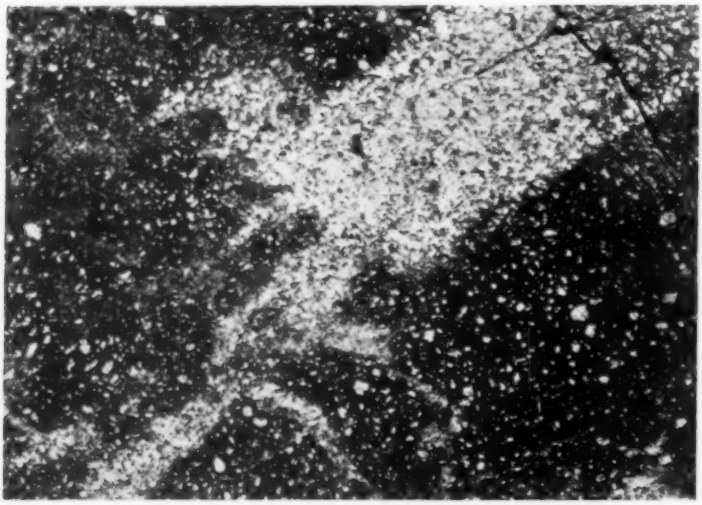


FIG. 1.—Photograph of a polished specimen (about 10×20 cm.) of the dike showing the irregular form of the coarser-grained products of magmatic residuals. The quartz, epidote, zoisite veinlets show as fine parallel lines with a lighter-colored portion on each side. The finer-grained patches on the left are recrystallized remnants of xenoliths.

One dike in which these features are most marked is not much over a foot in width and is well exposed on an old road about halfway between the Union Companion and Last Chance mines. It is nearly vertical, has a northwesterly strike, and traverses a schist roof pendant, the schistosity of which has a northerly strike. It resembles many of the fine gray porphyries of the district in having a few visible feldspar phenocrysts and minute flakes of mafics. It differs from them in that it contains inclusions of the country rock, a fine-grained, dark-colored biotite schist, and also in having very noticeably irregu-

lar coarser textured patches of the felsic constituents and many minute dark-colored, straight-line veinlets trending parallel to the walls of the dike (Fig. 1). The rock on each side of these veinlets, which are but a fraction of a millimeter wide, has been rendered lighter in color and more resistant to weathering, standing up about 0.5 mm. above the general surface. On polished surfaces the rock on either side of these veinlets for about a distance of 2 mm. is distinctly lighter in color. Where the veinlets are close together this lighter-colored, more resistant portion gives the appearance of a smaller parallel dike.

The larger plagioclase phenocrysts, making up about 10 per cent of the "normal" rock, are about 2 mm. in size and are basic andesine or even labradorite in composition. Owing to their excessive alteration, exact determination is difficult. Often they are almost completely obscured by kaolinite, flakes of sericite, and grains of epidote. These phenocrysts belong to an early generation. Some of them show gradational resorption. Some give indication that they were originally zoned with a composition of labradorite in the center and andesine on the outside. Many have a clear rim of later albite, which often shows a considerable extension.

A later generation of plagioclase phenocrysts, an oligoclase and esine, about 0.5 mm. in size, and unaltered, amounts to about 5 per cent. Zonal structure is characteristic of these feldspars, the centers being more calcic than the outer zones. Oscillatory zoning is common, more calcic plagioclase in the center, then a zone more sodic surrounded by another more calcic, and an outer sodic layer. Some of these later plagioclase phenocrysts have been formed around much altered centers of regular outline indicating smaller individuals, and some have been formed about partially resorbed feldspars of the earlier generation (Fig. 2). One of the latter cases shows a horseshoe-shaped remnant surrounded by the more sodic plagioclase, and it is interesting to note that a different section of this crystal might be interpreted as having a sodic center. Most of the later plagioclase phenocrysts show a rim of very sodic plagioclase, probably albite, which frequently extends into the groundmass, sometimes containing the quartz of the groundmass in poikilitic intergrowth (Fig. 3).

Some of the sections show one or two phenocrysts of a green py-

roxene partly altered to flakes of brown biotite. Green hornblende is present as phenocrysts in some of the sections, often showing coronas of brown biotite. There are also groups of brown biotite, thought to represent recrystallized earlier mafics, and, adjacent to some of the inclusions, biotite phenocrysts 1 cm. in size.

FIG. 2.—Photomicrograph of partially replaced green pyroxene. Showing less mafic zone around the crystal.

The groundmass is a fine-grained mosaic of plagioclase, quartz, flakes of brown and green biotite, which often show an alignment suggesting flow or gneissic structure, and other minor minerals such as magnetite, pyrrhotite, zircon, apatite, zoisite, epidote, chlorite, sericite, and kaolinite. Plagioclase makes up 50 per cent and quartz 30 per cent of the groundmass. From the foregoing it will be seen that the rock could be called a "quartz diorite porphyry."

FIG. 3.—Extension of outer albite zone on plagioclase phenocryst.

About 25 per cent of the dike consists of the coarser-textured patches, which are irregularly pitching lenses, either fairly regular in outline, or with intricate branching forms as if fluid magma had been forced into a partially solidified mass. In all cases thin sections show interlocking crystal contacts. The idea of pressure is further strengthened by the fact that the biotite in the groundmass is aligned parallel to these segregations. Sometimes there is an angularity to their contacts, suggesting fracturing of the recently chilled magma of the dike, the spaces between the fragments having been immediately filled with fluid residual magma.

In size the large segregations are 1–2 cm. thick and several centimeters in extent. The smaller lenticular quartz veinlets are about 3 mm. in width, often occurring as the more narrow end portions of the larger segregations. They have a general trend across the dike, and, where lenticular, are often roughly parallel to the schist inclusions. Some of the smaller, minute, bleblike quartz segregations occur adjacent to the larger partially resorbed andesine phenocrysts, and in one section are seen to have completely replaced an earlier feldspar. In composition the segregations are all more felsic than the main mass of the dike. Some consist chiefly of the older altered plagioclase phenocrysts, others are a coarser-textured aggregate of later more sodic plagioclase and quartz, and a few consist entirely of quartz. A gradation of all these phases in one segregation was noted, the older plagioclase being more abundant in the wider portions, while the narrow end stringers are nearly pure quartz. One of the segregations was found to consist of 85 per cent altered plagioclase phenocrysts 2 mm. in size, 15 per cent an interstitial quartz mosaic which in part contained interstitial grains of epidote. Another is made up of 50 per cent quartz, 40 per cent plagioclase with 10 per cent biotite.

FIG. 4.—Photomicrograph of quartz, epidote, zoisite veinlets.

In contrast to the irregular veins and segregations, the dike is traversed by minute, rather regular veinlets, 0.05–0.15 mm. in width trending parallel to the walls, consisting chiefly of quartz, epidote, and zoisite (Fig. 4). The latter two minerals are likely to appear where the minute fractures cut the altered plagioclase phenocrysts. Here too they enlarge slightly as if replacing the feldspar to a small extent. These quartz epidote veins are later than the irregular felsic veins, since they cut across them. They also cut some extremely minute veinlets of secondary silica that are noticeable in the feldspar. It is thought that these micro-veinlets of secondary silica may have been formed at the time of the kaolinization of the earlier generation of plagioclase phenocrysts, by endomorphic processes. Chlorite was

noticed in some of the veinlets, also magnetite, which occurred along the margins. From the quartz epidote veinlets there are almost submicroscopic, branching veinlets of chalcedonic silica. It is this network of veinlets which causes the rock on each side of a quartz epidote veinlet to have a greater resistance to weathering.

The schist fragments are very fine grained in texture, fresh fragments appearing nearly as dense as the groundmass of the dike, yet surface disintegration by weathering produces a rather friable, sometimes iron-stained material. They consist of a fine-grained intergrowth of about 60 per cent feldspar (andesine and unstriated feldspar), 25 per cent quartz, and 15 per cent biotite; the alignment of the biotite produces the schistosity. The term "leptynolite" might be applied to a rock of this type. They are identical to the feldspathic schists which compose much of the roof rock in this vicinity.

In the dikes the fragments are associated with felsic segregations, irregular veins, and biotite phenocrysts. The dike having the greatest development of these features has the greatest number of inclusions; one dike which has but a few inclusions shows veins developed only adjacent to the inclusions. Where recrystallized, the schistosity of the fragments may not be evident and they have the appearance of a fine-grained igneous rock.

Thin sections of contacts of the xenoliths are particularly interesting. Some show such a gradual replacement that it is almost impossible to note the exact contact, the schist grading imperceptibly into the porphyry, with the biotite in the groundmass aligned with the biotite of the inclusion. This may be an inherited structure, perhaps similar to that which Fenner noted on a large scale with regard to the assimilation of certain gneisses in the Highlands of New Jersey.[1]

Polished surfaces of contacts show a pulling out and strewing of minute fragments comparable on a minute scale to that described by Adams and Barlow in the Haliburton Bancroft area of Ontario.[2]

[1] C. N. Fenner, "Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII, No. 6, p. 594.

[2] F. D. Adams and A. E. Barlow, "Geology of the Haliburton and Bancroft Areas," *Department of Mines Memoir No. 6* (Ottawa, Canada, 1910).

This is also shown at the frequent contacts of the schist with the magmatic residuals and when they are highly silicic. Replacement seems to be evident, some sections giving the appearance of minute quartz blebs in a schist groundmass. Along some of the fragments rather small lenticular quartz veinlets are developed right at the contact, and in some they extend into the xenolith.

CONCLUSIONS

In outlining a working hypothesis for the mechanism which produced the peculiar features of these dikes, it is necessary first to consider the probable original character of the magma that formed the dike, and its relationship, both physical and chemical, to the parent magmatic mass.

The character of the earlier mafics and the rather basic plagioclase (an andesine-labradorite) of the older generation of feldspar phenocrysts in the dike, in contrast to the oligoclase of the normal granodiorite, suggest that the dike magma came from a more basic phase, located perhaps in a deeper zone of the batholith, or from an earlier more basic not yet differentiated batholithic magma.

The selective alteration, however, points to a deeper source for the dike magma. If it had been formed as an offshoot of an earlier more basic parent-magma, the volatiles given off during the fractionation of this magma might be expected to have altered the dike as a whole to some extent. The later feldspars and mafics, which are perfectly fresh, show that this is not the case. In either case, however, the striking alteration of the earlier-formed crystals might be explained by the change in equilibria or the release of volatile constituents with the lowering of pressure incident to the rise of the magma in the dike fissure.

The position of the dike is in the country rock near its irregular contact with the granodiorite, and roughly estimated to be perhaps 2,000 or 3,000 feet below the highest portion of the roof. Mine workings show that this portion of the roof is a typical roof pendant, an inverted pyramid in shape. The strike of the dike fissure is across the schistosity of the wall rock and roughly parallel to one side of the roof pendant.

Breaking as it did at an angle across the schistosity, it is natural

that many fragments of the schist wall were engulfed in the dike. Movement of these inclusions was probably hindered by the specific gravity and viscosity of the magma, as is indicated by the earlier-formed basic plagioclase and the alignment of some of the biotite, whether due to flowage or to crystallization pressure. In other words, these schist fragments were immersed in a pasty, partially crystallized, rather basic magma.

The walls and the fragments were probably at nearly the same temperature as the magma, as is shown directly by the fact that there is no evidence of differential chilling, no glassy borders, not even a finer-grained texture at the contact; and indirectly by the fractionation that subsequently took place in the very small system.

That the magma followed in general the reaction principle of Bowen seems to be indicated by the change from calcic to sodic feldspars and from pyroxene to hornblende and biotite.[1] However, oscillatory zoning and the peculiar segregations point to irregular differentiation. It seems that even the older feldspars and mafics reacted to such an extent with the liquid portion of the magma as to cause a rearrangement of the chemical constituents, causing local recrystallization and local impoverishment of certain constituents. Iron plus volatiles seem to have been readily abstracted from the magma immediately surrounding the original pyroxenes, changing them to hornblende and biotite, minerals of higher iron content and also containing the hydroxyl. There seems to be a corresponding lessening of biotite surrounding the recrystallized mafics. (Fig. 2).

In the schist fragments the transfer of iron from the magma tends to form larger, later phenocrysts of biotite or even small segregations of magnetite, so that a zone impoverished of iron becomes more silicic not only on account of the abstraction of the iron, but probably also by the actual transfer of silica to it from the magma and from the inclusions. The more silicic differentiates would therefore be initiated by the inclusions and controlled to a large measure by the speeding up of the reaction series. The segregation of the magmatic residuals would take place by what might be termed

[1] N. L. Bowen, "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX, No. 3; "The Behavior of Inclusions in Igneous Magmas," *ibid.*, No. 6.

"molecular transfer" depending upon the physical chemical characteristics of a varying complex system.

A diminution of volume would much facilitate this differentiation. That shrinkage did take place is shown by the fracturing of parts of the main dike with pegmatitic material filling in between the broken fragments of the dike. The silicic residuals, fluid on account of their fairly high content of volatiles, would not merely enlarge any initial zone of crystallization, but might also inject themselves through partially solidified magma in very irregular ramifications. In this way the association of the segregations with the inclusions, as well as their peculiar shape, would be accounted for.

The fact that some of the segregations consist of the older altered plagioclase with interstitial quartz may be explained by considering these older phenocrysts as remaining in the residual magma. The fact that they are almost completely altered to kaolinite, sericite, and secondary silica may be the reason for their failure to react or go into solution during the process of fractionation. Some of them did react and are nearly resorbed, and only the faintest remnants are left. There are also some small blebs of quartz adjacent to some of these older partially resorbed phenocrysts and some blebs which replace them entirely.

The silicic differentiates seem to be particularly efficient as replacing agents. Irregular veinlets extending into the schist fragment aided recrystallization, and prepared the material for ultimate absorption by the magma.

Pegmatitic phases associated with inclusions are rather common near batholithic contacts where the size of the intrusive mass and other physical factors, such as convection currents,[1] may obscure transitional phases. This small dike seems to show that segregations in a way analogous to pegmatitic segregations are but the results of the crystallization of the magma somewhat interfered with by its reaction with the schist inclusions. Other explanations for perhaps similar phenomena have been given, as, for example, the separation of the magma into immiscible liquid portions,[2] or it might be thought

[1] F. F. Grout, "The Vermilion Batholith of Minnesota," *ibid.*, Vol. XXXIII, No. 5, pp. 467–87.

[2] David Williams, "The Cronkley Mica Lamprophyres," *Proceedings of the Liverpool Geological Society*, Part IV, Vol. XIII, pp. 323–34.

that these veins were not indigenous. In a dike of this size the former explanation would be improbable, and the field relations show that the latter is not the case.

After the crystallization of the magma of the dike and its pegmatitic segregations and veins, minute cracks, thought to be tension cracks on account of their parallelism, were filled with the most liquid residue of the magma, forming the minerals quartz, epidote, and zoisite. That this residual portion of the magma was extremely fluid is evident by the minute cracks that it fills and by the still more minute branching micro-veinlets of secondary silica extending from the walls of these minute cracks.

In a large-scale intrusive mass the various steps in the crystallization may be so removed in time and space as to render their relationships a matter of conjecture. In the small magmatic system of 2-foot dike under not very rapid cooling conditions, the relationship of the various phases may appear more obvious.

The older altered phenocrysts are remnants of an earlier crystallization cycle. Probably by change of position the very end stages of this cycle were recorded in the alteration of the phenocrysts.

Then the newer magma reacted with the earlier-formed crystals, but was not able to absorb them completely, perhaps on account of the rate of cooling, which of course was more rapid than in a large mass, or on account of the loss of volatiles. The results of fractionation are shown in the mineral content of the "normal" porphyry, as, for example, the more sodic, later feldspars and the albitic rims which even extend as a sort of groundmass for smaller poikilitically included quartz crystals. There is no reason to believe that this dike, if undisturbed, would have been different from many of the fine-grained porphyries occurring in this vicinity.

Aside from those of deuteric origin, the dike appears to contain no minerals different from those formed by the undisturbed crystallization of the magma. Therefore the amounts and peculiar forms produced by the magmatic residuals are apparently the effect of the absorption of the schist inclusions.

THE QUICKSANDS OF BRAZOS COUNTY, TEXAS

FREDERICK A. BURT
Agricultural and Mechanical College of Texas

ABSTRACT

The quicksands of the area average the same mineral composition, texture, and degree of roundness as the non-quicksands. They are always supersaturated with water, which in some cases can be determined to be moving with upward current. The quicksand is not a type of deposit, but a condition of equilibrium.

INTRODUCTION

Brazos County is located in the Gulf Coastal Plain in east-central Texas about 100 miles north of Houston. The average annual rainfall of the county, as recorded by the state agricultural experiment station, is 38 inches. The run-off is taken care of by a large number of creeks, among which Turkey, White, Clifty, and Big have important quicksand deposits.

The formations of the county with which quicksands are associated are the Yegua and Jackson (both Eocene) and the Quaternary. The Yegua is typically a clay formation carrying many thin beds of lignite, and in its upper part some beds of sand. The Jackson is essentially arenaceous with some beds of clay. Some of the Jackson sands are not consolidated, but in many of the exposures they are seen to be cemented into sandstone or even quartzite.

The Quaternary formations are divided into terrace deposits (Pleistocene?) of gravel, sand, and clay and flood-plain deposits (Recent). The latter are often of heavy clays, but where associated with quicksands are always arenaceous.

GEOLOGIC RELATIONS OF THE QUICKSANDS

Quicksands of much depth and treacherous character are located in the flood-plain deposits along the margin of the Brazos River. These are too thick to be penetrated with a hand drill and hence nothing concerning their base has been determined. They consist of

red sands of no different type from those composing the other flood-plain deposits. North of Jones Bridge a patch of these quicksands is intimately associated with springs, intimating that upward water currents are a factor in developing their quick character, as suggested by Gow.[1]

Along White Creek and its tributaries quicksands are of some importance in small patches. Near the head its tributaries are cut in the base of the Jackson formation. Farther down they are cut in the Pleistocene terrace deposits. The contact of the terrace formation with the underlying Yegua is an irregular one and in average

FIG. 1.—Generalized profile of bed of White Creek and its southern tributaries. *Y*, Yegua; *J*, Jackson; *Q*, Quaternary.

level it is close to the stream bottom, as shown in Figure 1. The quicksand deposits are without exception located within the areas of shallow Quaternary deposits where the underlying Yegua clays have given rise to perched water tables.

In Turkey Creek the relations of the valley bottom to the terrace formations and the Yegua are much the same as in White Creek and its tributaries. The average depth of the valley is close to the average thickness of the Quaternary in this part of the county. Small quicksand deposits are numerous and bear much the same relation to the formation contacts as along White Creek. In the late summer and fall the sands along the valley bottom completely dry out except for the deeper, larger quicksand patches which always retain water and thus become distinctly marked to the eye by greenish algae and other vegetal growths.

Clifty and Big creeks in the southern part of the county have more shallow, open valleys cut in the Jackson formation. Small deposits of quicksands occur along these creek bottoms above the clay layers of the formation wherever they produce perched water tables.

[1] C. R. Gow, "Quicksand: Its Nature, Behavior, and Control," *Canadian Engineer*, Vol. XXXIX (1920), pp. 392–95.

PROPERTIES OF THE QUICKSANDS

Quicksands from various depths have been collected from Turkey, White, and Clifty creeks and their tributaries and the Brazos

FIG. 2.—Camera lucida drawing of fragments from the Turkey Creek quicksands, 8-inch depth.

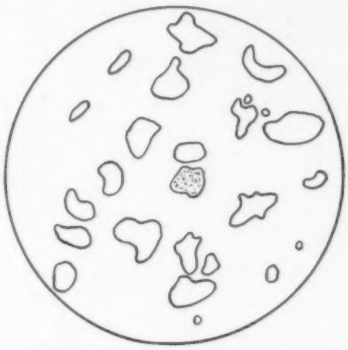


FIG. 3.—Camera lucida drawing of fragments of the White Creek quicksands, 10-inch depth.

River (Figs. 2–4). The collections utilized in this study were made during the dry season when the stream beds were hard and no water was visible on the surfaces of the quicksand patches. Samples were obtained by means of a hand auger. To keep the sands from different levels separate it was necessary to sink a 2-inch iron pipe into the deposit after the manner of a well casing. The casing was made to follow the auger down so that each core of sand withdrawn was taken from the base of the casing.

FIG. 4.—Camera lucida drawing of fragments of the Turkey Creek quicksands, 24-inch depth.

In these creeks the quicksands are predominantly of quartz, with small but conspicuous amounts of magnetite. Limonite grains, broken selenite crystals,

corroded feldspar fragments, and diatom tests also occasionally occur. The ratio of the magnetite to the quartz has been obtained by removal of the former with a magnet. The sands were weighed before and after removal of the magnetite and the percentage of magnetite in the original sand calculated. Each of the results tabulated in Table I is an average of ten determinations, each of from 200 to 900 milligrams of sand.

TABLE I

MINERAL CONTENT OF THE QUICKSANDS

	Turkey	Turkey	Clifty	White
Depth of sample in inches	8	24	18	18
Percentage of quartz present	99.505	99.440	98.820	99.560
Percentage of magnetite present	0.495	0.560	1.180	0.435
Percentage of total quicksand	100.000	100.000	100.000	99.995

An analysis of the Turkey Creek quicksand was made to determine the percentages of sand and water in them under ordinary autumn conditions when the valley bottom was dry. After weighing the samples in the condition in which they were withdrawn, they were completely desiccated and the dry sands weighed. The original

TABLE II

RATIO OF WATER AND SAND TO TOTAL QUICKSAND

	8-Inch Depth	18-Inch Depth	36-Inch Depth
Weight of quicksand	120.600 g.	217.080 g.	168.622 g.
Weight of desiccated sand	93.260 g.	158.542 g.	127.478 g.
Weight of evaporated water	27.340 g.	58.538 g.	41.144 g.
Proportion of sand by weight	77.33%	73.03%	75.60%
Proportion of water by weight*	22.67%	26.97%	24.40%
Proportion of sand by volume	56.07%	50.31%	53.67%
Proportion of water by volume	43.93%	49.69%	46.33%

* Reduced to volume, $V = \frac{M}{D}$ where $D = 2.675$ and M = weight.

amount of water was computed from the loss of weight. The calculations of the percentages of sand and water in the quicksands, in terms of volume, were made from their weights on the basis of the specific gravity of the water as 1 and the sand as 2.675 (the specific gravity of a mixture of SiO_2 and Fe_3O_4 in the ratio in which they occurred in the sand). The results are recorded in Table II.

The percentages of the normal pore space of the Turkey Creek quicksands were obtained by weighing a total of 69.945 grams of the desiccated sands from the 8-inch depth. These were measured and allowed to settle under their own weight with gentle tamping at intervals. The pore space was then computed from King's[1] formula, $100\,\frac{Vd-W}{Vd}=P$, where P = volume in cubic centimeters, d = specific gravity, and W = weight in grams. The results obtained gave the

TABLE III

PERCENTAGE OF SATURATION OF QUICKSANDS

	8-Inch Depth	18-Inch Depth	36-Inch Depth
Water by volume in 100,000 parts	4,392	4,969	4,633
Pore space in 100,000 parts	4,150	4,150	4,150
Percentage of saturation of pore space	105.85%	119.73%	111.63%

TABLE IV

MECHANICAL ANALYSES OF SANDS

Sands Retained by Screen (Mesh per Inch)	Turkey Creek Quicksand, 8-Inch Depth (Percentage)	Turkey Creek Quicksand, 18-Inch Depth (Percentage)	Turkey Creek Non-Quicksand, 8-Inch Depth (Percentage)	Clifty Creek Quicksand, 18-Inch Depth (Percentage)	Clifty Creek Non-Quicksand, 18-Inch Depth (Percentage)	Brazos River Quicksand, 26-Inch Depth (Percentage)
20	1.01	0.62	1.82	0.24	1.51	3.79
40	1.01	14.02	10.02	0.36	1.75	12.66
60	10.12	12.15	11.03	4.48	4.50	51.90
80	27.12	24.92	28.12	18.40	20.03	24.36
100	18.22	18.07	17.51	28.21	26.67	5.16
Finer than 100	42.51	30.21	31.50	48.31	45.54	2.13

sand a pore space of 41.5 per cent. Experiment by the same method on sand from the 18- and 36-inch depths gave the same result in the first decimal place. The amount of the supersaturation of the quicksands in nature is shown in Table III.

The results of screening sands is shown in Table IV. The percentages (in volume) are reckoned to the nearest whole figure in the second decimal place and represent the screening of about 1,000 cc. each of ten samples from each locality.

[1] F. H. King, "Movements of Underground Water," *U.S. Geol. Survey Annual Report 19*, Part II, p. 208.

After studying the shapes of the quicksand grains (Figs. 2, 3, and 4) the Columbia University Laboratory method was employed for determining their coefficients of roundness. Following this method field samples were collected and small sections of the sand isolated, care being taken that the sample should not lose any of its contents by running and thus suffer a selective loss. The samples were placed under a low-power compound microscope and the grains separated into five groups labeled angular, subangular, half-round, subround, and round. The number of grains in these classes were multiplied by the following numbers, respectively: 1, 2, 8, 32, 128.

TABLE V

COEFFICIENTS OF ROUNDNESS OF VARIOUS SANDS

Sand	Location	Coefficient of Roundness
Oölitic	Pyramid Lake, Nevada	66.10
Dune	Southern California	47.77
Quicksand	Turkey Creek	44.00
River (not quick)	Turkey Creek	43.66
Quicksand	Clifty Creek	35.15
River (not quick)	Clifty Creek	33.12
Quicksand	White Creek	32.68
Beach	Charleston, South Carolina	28.56
Beach	Manchester, Massachusetts	17.30
Volcanic	Lassen Peak, California	2.21

The products were then added and the sum divided by the whole number of grains. The quotient was recorded as the coefficient of roundness. The results of the grain counts are given in Table V. Several samples of sands of different type are given for purposes of comparison.

CONCLUSIONS

The data gathered on the quicksands of the county seem to warrant the following conclusions:

1. They are invariably associated with perched water tables.

2. They possess a high degree of roundness; but this is not as high as oölitic and some other sands not of quick character, and is on the average not much higher than that of the non-quicksands associated with them. In fact the smoothness of the grains is more conspicuous than their roundness.

3. They are in general fine, but no finer than many non-quicksands.

4. Their grains are not of uniform size, but show a considerable range.

5. Their mineral composition is not different from that of the non-quicksands associated with them.

6. They are supersaturated with water which may be largely expelled by pressure.

7. On expulsion of their water they become as firm as the most compact sands.

8. Their property of quickness is due to their supersaturated condition, which in turn is due to their relation to the local groundwater conditions.

EDITORIAL

THE WORK OF WALCOTT

Charles Doolittle Walcott did many things and did them well but his persistent effort to elucidate the earth's earliest record of life will be his lasting monument. His choice of this field was strategic. No faunas of the past mean so much to those who want to know the salient things about the history of life on our planet. Our base line for projecting estimates into the great unrecorded era of primitive life has its distal end on the Cambrian fauna and its proximate end on the life of today. Walcott worked with a success equaled by no other in giving a definite placement to the farther end of this base line. The revelations of its nature that rewarded his search in his later years were quite beyond the fondest expectations. He found evidence that, as long ago as the Cambrian, life bore many features closely like those of the life of today. These revelations have made clear that the life of that day was very far from being "primordial." The base line must be multiplied many times before the true primordial life can be reached.

The great significance of Walcott's work lies in this determination. The wonderful record of details of life structure he was so fortunate as to recover—perhaps we should say he had the acumen to uncover—make his contribution secure and explicit. His monument rests on a solid foundation. Its value as a standard of measurement will be better realized as time goes on and the real age of the earth and the slowness of life evolution comes to be more fully appreciated.

T. C. C.

REVIEWS

The Geology of South Africa. By ALEX. L. DU TOIT. Edinburgh: Oliver & Boyd, 1926. Pp. 463, pls. 39, text figs. 64, geological map.

Though primarily covering the states of the South African Union, this admirable book gives welcome data regarding the Bechuanaland Protectorate, South West Africa, Portuguese East Africa, and Southern Rhodesia—a total area of nearly 1,200,000 square miles, or one-third of the area of the United States. The well-executed geological map represents an extension of the four-sheet wall map of the Union, recently issued by the Geological Survey at Pretoria. The book illustrates the enormous advances made by a handful of workers within the last two decades, since the publication of *The Geology of the Cape Colony*, by Rogers and du Toit, and *The Geology of South Africa*, by Hatch and Corstorphine. Stimulated by a long succession of sensational discoveries and aided by a general absence of forest cover, these few observers have already proved themselves to be among the great masters of *reconnaissance* geology. Recent memoirs of the Union Geological Survey show, moreover, the power of South African geologists in detailed mapping and discussion. Gifted with a remarkably keen eye, an astonishing memory for outcrops, and great energy, du Toit must himself be rated high in this splendid group of path-breakers. His thoroughness in field work is matched by the completeness with which he has digested the extensive literature of his subject. By a judicious use of two fonts in printing he has been able to introduce into a handy volume an astonishing amount of information.

The text is of necessity chiefly stratigraphic, but the author is always alive to the questions of structure. One of the reasons why his story should interest geologists of the Northern Hemisphere may be illustrated by a quotation: "Nearly every important break in South Africa, palæontological as well as stratigraphical, happens to fall somewhere within one of the European Systems, and each more or less well-marked unconformity between the Systems in the Northern Hemisphere is usually represented in this country by continuous deposition." When these two facts are truly explained we may be able to understand the tectonics of North America!

Chapters xviii, xix, and xx deal respectively with "Primitive Man

in South Africa," "The Soils," and "Economic Geology," while the closing chapter gives a clear and engaging geological history of the vast country.

Among the details may be mentioned: the tremendous thickness of the stratified systems; a small but instructive tectonic map of the whole region; the dating of the "Cape Foldings" (a satisfactory name for the southern mountains is not in hand—will "Cape Cordillera" serve?); the richness of the igneous phenomena; the significant alignment of the marvelous Vredefort dome, the Bushveld Complex, and the 300-mile "Dike" of Rhodesia; the basaltic floods and doleritic intrusions of Karroo age and their relation to orogeny; the redefined Waterberg system and recognition of the importance of the unconformity at its base; the good summary of the stratigraphy and unique paleontology of the Karroo system, including its famous reptiles; a thorough digest of the Cretaceous system; recognition of several tillites, much older than the Dwyka, which is shown to be of Carboniferous date; discussion of the origin of the "alkaline" rocks, of kimberlite and diamonds, peridotite-norite and platinum, Witwatersrand gravels and gold; and an all-too-brief statement of du Toit's views regarding continental migration.

The publishers are to be congratulated on the style of the book-making. They also have helped in making the work a model for regional handbooks. Among the many fine illustrations may be specially noted the photographs of the Table Mountain series and its spectacular unconformity with older granite, Dwyka tillite, erratics, striated boulders, and boulder pavements, the grand basaltic cliffs of the Drakensberg, and the diamond mines.

The Geology of South Africa is timely for two reasons. It brings up to date the story of a region which is as unique in illustrating principles of geological science as it is in the field of economics. South Africa has few rivals among the countries which are today most advancing the science, and clearly no American geologist can afford to be ignorant of the many discoveries and stimulating problems coming out of southern Africa. Every geologist worthy of the name realizes that he must strive to know, not his home ground alone, nor his own continent alone, but as far as possible, the whole earth. Du Toit's service is great, therefore, in issuing so perfect a survey of one of the most instructive parts of the planet. Secondly, this book will be specially valued by those who intend to join the International Geological Congress of 1929, advertised to meet in South Africa during the superb months of July and August. The volume serves as a notably complete introduction to that land of geological wonders.

REGINALD A. DALY